Out of this word: the effect of parafoveal orthographic information on central word processing

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2009

Abstract

The aim of this thesis is to investigate the effect of parafoveal information on central word processing. This topic impacts on two controversial areas of research: the allocation of attention during reading, and letter processing during word recognition. Researchers into the role of attention during reading are split into two camps, with some believing that attention is allocated serially to consecutive words and others that it is spread across multiple words in parallel. This debate has been informed by the results of recent experiments that test a key prediction of the parallel processing theory that parafoveal and foveal processing occur concurrently. However, there is a gap in the literature for tightly-controlled experiments to further test this prediction. In contrast, the study of the processing that letters undergo during word recognition has a long history, with many researchers concluding that letter identity is processed only conjointly with letter 'slot' position within a word, known as 'slot-based' coding. However, recent innovative studies have demonstrated that more word priming is produced from prime letter strings containing letter transpositions than from primes containing letter substitutions, although this work has not been extended to parafoveal letter prime presentations. This thesis will also discuss the neglected subject of how research into these separate topics of text reading and isolated word recognition can be integrated via parafoveal processing.

It presents six experiments designed to investigate how our responses to a central word are affected by varying its relationship with simultaneously presented parafoveal information. Experiment 1 introduced the Flanking Letters Lexical Decision task in which a lexical decision was made to words flanked by bigrams either orthographically related or unrelated to the response word; the results indicated that there is parafoveal orthographic priming but did not support the 'slot-based' coding theory as letter order was unimportant. Experiments 2-4 involved eye-tracking of participants who read sentences containing a boundary change that allowed the presentation of an orthographically related word in parafoveal vision. Experiment 2 demonstrated that an orthographically related word at position n+1 reduces first-pass fixations on word n, indicating parallel processing of these words. Experiment 4 replicated this result, and also showed that altering the letter identity of word n+1 reduced orthographic priming whereas altering letter order did not, indicating that slot-based coding of letters does not occur during reading. However, Experiment 3 found that an orthographically related word presented at position n-1 did not prime word n, signifying the influence of reading direction on parafoveal processing. Experiment 5 investigated whether the parallel processing that words undergo during text reading conditions our representations of isolated words; lexical decision times to words flanked by bigrams that formed plausible or implausible contexts did not differ. Lastly, one possible cause of the reading disorder dyslexia is under- or over- processing of parafoveal information. Experiment 6 therefore replicated Experiment 1 including a sample of dyslexia sufferers but found no interaction between reading ability and parafoveal processing. Overall, the results of this thesis lead to the conclusion that there is extensive processing of parafoveal information during both reading (indicating parallel processing) and word recognition (contra-indicating slot-based coding), and that underpinning both our reading and word recognition processes is the flexibility of our information-gathering mechanisms.

Declaration

I declare that this thesis was composed by myself, that the work it contains is my own, and that this work has not been submitted for any other degree or professional qualification except as specified.

Date:

Signed:

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Contents

Chapter 1
Introduction

Why study word recognition and reading?

For most literate adults, reading is an activity that is as much a part of everyday life as walking or laughing. The fluency and speed of reading (approximately 200-250 words per minute) is all the more remarkable given that the recent development of writing systems (they are about 4,000 years old) means that we have not evolved for reading skill. We take for granted the ease with which we convert written symbols into a meaningful and coherent communication from a person whom we might never meet, and yet our ability to carry out this deceptively simple task is dependent upon the interaction between sophisticated vision and language systems. It is this coupling of visual and language processing that intrigues reading researchers, and knowledge of both fields is required to make sense of the eye movement patterns produced when we read and the reactions produced when we respond to individual words.

One of the ways that we approach this daunting task is to equate reading with an earlier form of language communication that was in spoken form. Given that spoken language developed prior to written language, how much does the medium in which language is conveyed influence our language processing? Unpacking speech obviously requires many of the same language processes as decoding writing, from recognising words to sentence comprehension to completing text-level anaphoric references. However, the presentation of speech is necessarily serial, with speech sounds vocalised and heard across time, and speech researchers include a phonological buffer (Baddeley, Lewis, & Vallar, 1984) in many speech models to facilitate the necessary short-term memory storage of uttered sounds. Writing, on the other hand, is a permanent record of language that allows the reader to re-sample its content at will and therefore does not initiate the same memory demands. When processing speech, the listener is a relatively passive recipient of the audio information being presented, although speech does provide some clues to the identity of upcoming words, for example through co-articulation effects. When reading, the reader can implement an active and flexible approach to gathering visual information. Speech perception, which requires an interaction between the audio and language systems, can be characterised as temporal, whereas as described above reading is an essentially spatial activity that can take advantage of the properties of our visual system and our attention-led ‘roving eyes’.

However, there is some debate in the reading and word recognition literature as to the flexibility of our lexical and letter processing mechanisms. When reading, its spatial nature means that there is the possibility of processing both the currently fixated word and its surrounding words. Specifically, how much information is extracted from outside the word currently undergoing fixation? This question applies both to words in text that are always presented alongside other words, and also to isolated words, whose easily controlled presentation has led to their widespread use for testing the mechanisms of lexical access. Similarly, when viewing individual words there is the possibility of determining the identity of their component letters without necessarily processing their order, unlike in speech whose temporal nature automatically conveys the identity of letters in a particular sequence. The question for this thesis is whether we avail ourselves of the possibilities for information gathering that visual language provides, or whether our language input mechanisms are dominated by speech to the extent that reading and word recognition are restricted to acting as the visual analogue of auditory language processing.

A second question concerns the relationship between isolated word recognition and reading. Improving technology and innovative thinking has led to the invention of multiple methods for studying word processing and reading. Isolated word recognition is indexed primarily by reaction time speed when completing a decision as to whether a string of letters constitutes a word or not (lexical decision), naming a word or categorising it according to set criteria. Reading processes are accessed via the study of the eye movements produced while a participant reads for comprehension. An alternative source of information comes from scanning the brain while either of these tasks is performed. The results of these methods are often used to clarify and refine models of lexical access or eye movement control during reading, and testing the assumptions on which these models are based in turn prompts further experimental work.

While isolated word processing and reading are different tasks, they overlap in some aspects, and isolated word processing has historically been used as a simplified method for studying the word recognition component considered common to both tasks. However, the two are now often studied separately, with individual models and methodologies, and researchers from one field do not always cross-reference their findings with those from the other field. This has led to lost opportunities for assessing the nature of the lexical access component of reading, and the impact of text-level factors on the representations of isolated words. One way to tie these two topics together is by testing the impact of varying parafoveal information when reading or processing isolated words and analysing the similarities or differences between the reactions produced.

Aims of the thesis

This thesis has several aims. Its primary aim is to investigate how parafoveal information can influence lexical access during reading and word recognition. One way that it will achieve this is via the use of a novel form of priming, spatial priming, in which the prime information is presented at the same time as the target but at a different location. Specifically, this work will focus on whether there is orthographic priming from parafoveal letters on foveal word processing as a direct measure of the impact of parafoveal information. This simple question has important theoretical ramifications for both text reading and isolated word recognition. In the former, whether parafoveal and foveal processing can occur simultaneously is a contentious issue for researchers designing models to simulate the eye movements that occur during reading, as if they can co-occur this is evidence in favour of parallel processing. In the latter, orthographic priming from letters presented in peripheral vision provides support for the models of word recognition predicated upon the assumption that letter identity can be coded separately from letter position.

As mentioned above, this thesis will also discuss how the topics of isolated word recognition and text reading can be brought together, with a summary of the work carried out so far and with experiments that combine aspects of both. It will address how the similarities and differences found contribute to our understanding of both the shared elements of the two tasks and the important ways in which the paradigm employed by researchers influences the responses produced. Lastly, reading is not always the automatic process that it appears to be for fluent readers, and the most prominent type of reading disorder is dyslexia, characterised by persistent difficulty with reading despite adequate cognitive faculties and external support. There is some evidence to suggest that parafoveal information processing could be an issue in dyslexia, and this thesis will explore this possibility using the spatial priming paradigm.

Chapter 2
Literature Review

Introduction

Reading is a complex process that requires input from visual and linguistic systems; as such, it is no surprise that it is a topic of major interest for researchers of vision and psycholinguistics. Additionally, the desire to simulate the mapping of orthography to phonology required for reading aloud was one of the motivating factors behind the development of connectionist modelling principles. This tradition of modelling reading processes continues today, as does the awareness of the need to integrate information from within and outwith the reading research field. Research into reading is an ongoing process, covering isolated words and text, models and human experimental data, eye movements and reaction-time tasks; this literature review aims to give both a brief history of these topics and a snapshot of the 'state of the art' in this field. As the purpose of this PhD is to investigate orthographic processing in parafoveal vision this review will commence with an outline of the letter-level input to models of isolated word recognition. It will then provide an overview of models of eye movement control during text reading, and will next focus on the processing of parafoveal stimuli and how this has provided evidence for and against parallel processing in reading. Lastly, it will discuss the need to integrate techniques and findings from single words and words in text.

Models of word recognition: Slot-based coding

When we are presented with a word we face the task of fixating on an informative part of the word, encoding its features, converting these into letters and then connecting this letter pattern with a stored lexical item in order to recognise this word and respond in the appropriate manner. The third part of this process, the letter-level encoding, is considered to be the first language-specific stage following low-level oculomotor and visual processing. It has become one of the key aspects differentiating the many models of isolated word recognition that have been proposed. These models are typically required to reproduce human data on reading aloud an isolated word. Constructing a model to test a theory forces researchers to examine and question any assumptions present in the theory; models can also produce testable hypotheses that can be verified (or not) via human data collection.

There are two basic properties of the letter within a word that must be encoded: letter identity (what it is) and letter position (where it is). That the identity of letters must be elucidated is less controversial (e.g., Pelli, Farell, & Moore, 2003), but the way the position of the letters is encoded is more problematic. An obvious approach to letter encoding is to have a set of 26 input units, one for each letter of the alphabet, at every possible letter position (theoretically unlimited). This slot-based coding means that every letter is processed within its position in a word independently of any other letters. The other extreme is distributed coding using a single set of letter input units simultaneously activated across the whole word. With distributed coding, the identity of each letter is processed independently of letter position. The dilemma is one of accuracy versus flexibility: in order to be able to differentiate between anagrams (e.g., *top* and *pot*) letter position must be encoded but if the coding is too rigid then learning dependencies between letter positions are restricted.

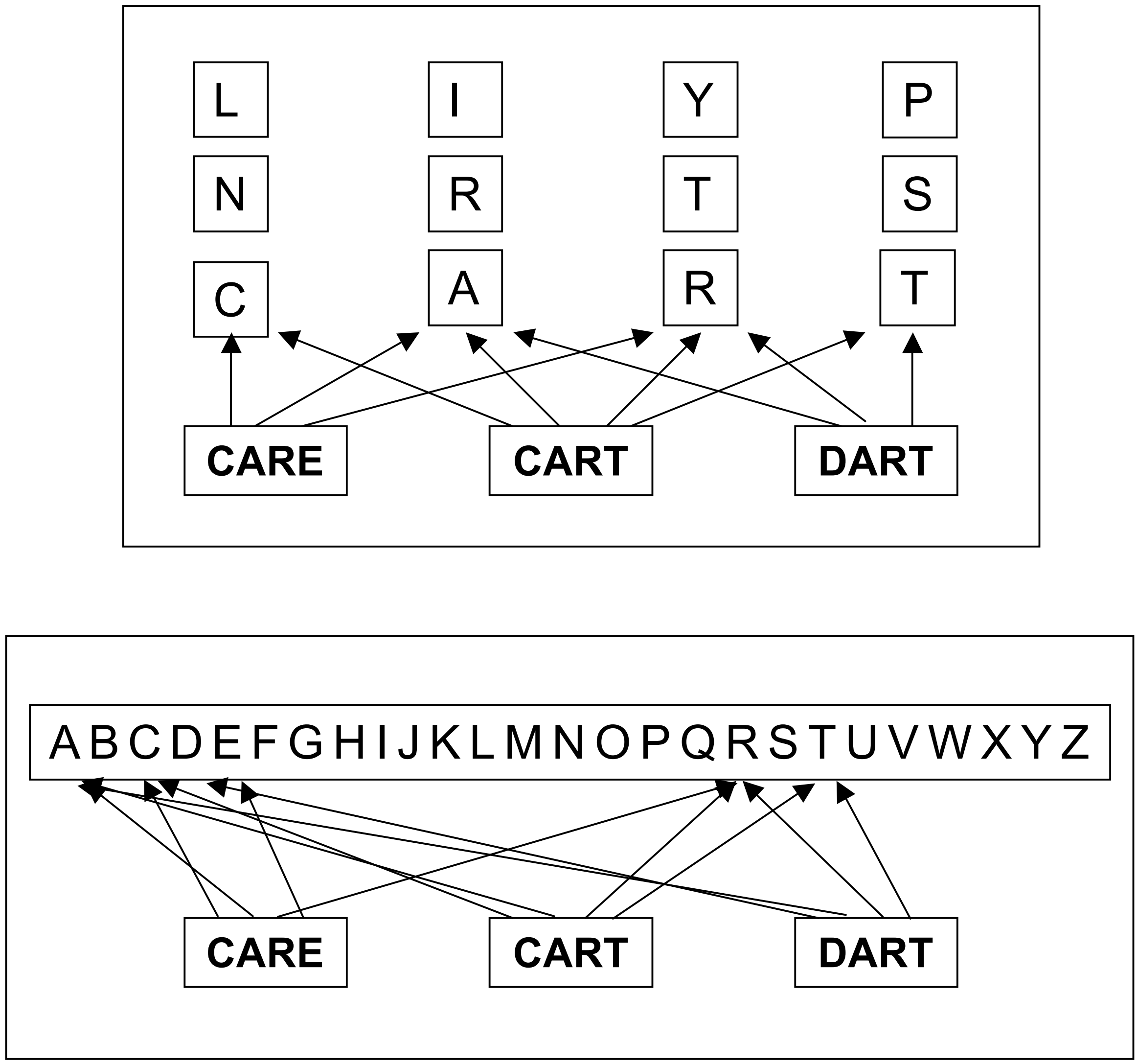

FIG. 1: Schematics of slot-based coding (top) and distributed coding (bottom)

This dilemma is exemplified in the history of models of isolated word recognition (see Grainger, 2008). An early and extremely influential model was the Interactive-Activation Model (IAM; McClelland & Rumelhart, 1981) that is a proto-connectionist model designed to account for the word superiority effect, the finding that letters are easier to recognise in words than in isolation (e.g., participants are quicker to recognise the letter *r* when it is in the word *frog*; Reicher, 1969). It was the first word recognition model to include an element of interactive processing via top-down feedback from the word-level back down to the letter-level. This model uses the extreme version of slot-based coding for its letter input system with a different layer of letter units for each position in a word. The advantage of this system is that its maximal information extraction allows for easy distinction between anagrams as there is no ambiguity in the input.

Since the IAM there have been many models based on the principles laid out by McClelland and Rumelhart (1981) that have taken advantage of this simple input system. Examples include the activation-verification model (Paap, Newsome, McDonald, & Schvaneveldt, 1982), the multiple read-out model (Grainger & Jacobs, 1996) and the dual-route cascaded model (Coltheart, Rastle, Perry, Ziegler, & Landon, 2001). The model of Seidenberg and McClelland (1989) used a modified slot-based system whose input was triples of graphemes, or Wickelfeatures (Wickelgren, 1969). For example, the word *done* is specified by the triples *#do*, *don*, *one*, and *ne#*, where # is a blank space. As at least one neighbour of each grapheme is specified this allows for some relative position-specificity due to immediate neighbour letter context.

These models have successfully captured a range of effects found in the human behavioural data but their input style has been the subject of much criticism. Although the conjunctive coding of letter identity and position is very accurate in its task it is inflexible, redundant and inefficient. There is no generalisation from the pronunciation of a letter learned in one position (e.g. the *l* in *log*) to the pronunciation of the same letter in another position (e.g. the *l* in *bulb*; this is known as the dispersion problem; Plaut, McClelland, Seidenberg, & Patterson, 1996). The IAM in particular restricts the length of the words that can be presented to the model, and does not allow for influences between words of different lengths, such as *claw* and *law* (Brysbaert, 2004). Repetition of a letter within a word is no different: the initial *t* in the word *tent* is learned independently from the final *t* with no overlap (Bowers, 2002) as letters are learned solely within their specific word context as a letter-in-position. In the Seidenberg and

McClelland (1989) model there is no learning even from the *t*'s in *time* and *this*, as although they are in the same position within the word they are coded by the unrelated units *#ti* and *#th*. These models are prevented from easily learning the regularities that are prevalent in language systems, even in a language with deep orthography such as English (McLeod, Plunkett, & Rolls, 1998).

Models of word recognition: Moving on from slot-based coding

As discussed above, the other extreme in the trade-off between accuracy and flexibility is to have a distributed set of position-independent letter units. It is immediately apparent that a completely distributed system would be unable to distinguish between anagrams as it produces no letter position information. Plaut et al. (1996) circumvented this problem in part by exploiting the letter ordering constraints inherent in monosyllabic English words in their revised version of the Seidenberg and McClelland model (1989). Monosyllabic words are typically composed of a consonant cluster (onset) followed by a vowel (nucleus), and then another letter cluster/single letter (coda). This effectively creates a three-slot system but with strong constraints on ordering within each position (e.g., if both *s* and *t* are present in the onset cluster, *s* must precede *t*). However, Bowers (2002) pointed out the Plaut et al. model still treats the *t*'s in *tent* as unrelated. All slot-based models also suffer from the alignment problem, the inability to recognise familiar stimuli when they are presented in an unfamiliar position. To use the example from Bowers, a model's familiarity with the words *cat* and *pole* are of no consequence if it encounters the complex word *catpole*.

The limitations discussed so far would seem reason enough to discount slot-based coding and reliance on absolute letter positions as viable solutions to the problem of letter input coding in models of isolated word recognition. However, there is a further set of data that the models discussed so far cannot account for and that more recent models attempt to simulate (Grainger, 2008). These data come from experiments assessing the responses to stimuli formed from the letters of a word but with slight alterations to their order or length. A letter of the original word (e.g., *clock*) is substituted by another letter (to form *tlock*), letters are transposed within the word (to form *colck*), or letter are removed altogether (to form *clck*); comparing the effects of these different alterations allows for analysis of the independent effects of letter identity and order. These stimuli are either presented as part of a lexical decision/naming task or used as primes in the masked priming paradigm (Forster & Davis, 1984). Experiments have been carried out in Spanish (Perea and colleagues) and French (Grainger and colleagues) as well as in English, with similar conclusions drawn from all three languages.

The most common comparison is of substituted-letters (SL) stimuli with transposed-letters (TL) stimuli: in the former letter identity is altered and in the latter letter order is altered. Chambers (1979) assessed the impact of these alterations on lexical decision times to non-words that were either orthographic neighbours (letter strings that differ from each other by one letter) or anagrams of high frequency words (e.g., *lotor* and *omtor* from *motor*). She found that while reaction times to the SL non-words did not differ from a matched non-word those of the TL non-words were significantly slower, suggesting that there was interference from the high-frequency word whose representation was automatically activated only by the TL non-words. Similarly, Andrews (1996) found that both lexical decision and naming were impaired for the higher frequency member of high-low frequency TL word pairs (e.g., *salt*/*slat*) compared to matched controls. She noted that results of this type provide important constraints on the input to models of isolated word recognition, as for models using slot-based coding TL neighbours differ markedly from their baseline word (e.g., IAM; McClelland & Rumelhart, 1981); similarly, for models that rely on wickelfeatures there is no overlap between four-letter TL words and their neighbours (Seidenberg & McClelland, 1989).

Andrews (1996) also carried out a masked priming version of this work by briefly presenting one member of the TL pair as a prime for the other member, revealing that naming accuracy was reduced compared to a control word. Several other studies have combined masked priming and TL stimuli (Forster, Davis, Schoknecht, & Carter, 1987; Lupker, Perea, & Davis, 2008; Perea & Lupker, 2003, 2004). Details of these experiments will be discussed in Chapter 6 but the typical finding is that TL primes provide similar levels of facilitation to identical primes, and significantly more than SL primes. In other words, a letter string containing all of the same letters as a baseline word (even if they are out of position) is more similar to that baseline word than a letter string containing only some of the same letters. This result is contrary to the predictions of slot-based coding models in which letters are processed only within their specific position-determined channel: these would predict equal levels of priming from TL and SL primes as they contain identical numbers of correct letters in their correct positions. For example, there is no more overlap for the TL prime *qucik* than the SL prime *qatik* with the target word *quick* as only letters 1, 4 and 5 are identical in both.

A variation on TL priming is relative-position priming (RP) when letters are removed or characters added so that the prime does not contain all of the letters of the target word but the relative order of the remaining letters is preserved. If a target word is five letters long (12345 or *train*) then an RP prime might be 1245 (*trin*). From the findings obtained using this paradigm it appears that relative position is key. For example, Humphreys, Evett, and Quinlan (1990) found significantly more priming for 1245 (*trin*) masked primes than 1435 (*tian*) primes in a perceptual identification task. Critically, adding filler characters to the RP primes (1q3q5 or *tqiqn*) to reinstate absolute position and length information does not increase priming, but a lexical decision task showed that when relative position is violated priming disappears (Grainger, Granier, Farioli, Van Assche, & van Heuven, 2006; Peressotti & Grainger, 1999). This is true for words up to 9 letters long and priming is even observed when the prime shares less than 50% of the target's letters (e.g., four letter prime for a nine letter target), again provided that relative letter order is maintained (Grainger et al., 2006). RP priming also provides evidence for the primacy of individual letter units: factors such as word shape and length are lost in an RP prime (Grainger et al., 2006), as is the onset-nucleus-coda pattern of most words utilised by Plaut et al. (1996) in their model.

The evidence presented above leads to the conclusion that whereas letter identity and the relative position of letters are important, absolute letter position that is dependent on word length is less so. This explains the ease with which we can read 'jumbled words' (Grainger & Whitney, 2004) and highlights the limitations of depending on strict slot-based coding. The comparative importance of encoding letter identity over absolute letter order is demonstrated by an analysis carried out by Shillcock, Ellison, and Monaghan (2000). They showed that if the letters of a word are split into only two slots about the midpoint (e.g., *card* split into *ca* and *rd*) then 98.6% of words can be unambiguously identified without any further ordering information. Any successful model of isolated word recognition must incorporate an input level that is flexible and tolerant of noise, and capture subtle effects such as the role of exterior letters (the *t* and *n* in *train*) and the tolerance of extreme letter transpositions (e.g., *acpmiset* from *campsite*). Recent models of isolated word recognition have attempted to do just this, and all emphasise the contribution of letter identity and relative position information.

Models of word recognition: Recent models

The models that will be presented in this section are SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003), the overlap model (Gómez, Perea, & Ratcliff, submitted), the split-fovea model (Shillcock & Monaghan, 2001) and SOLAR (Davis & Bowers, 2006). These models fall into three rough categories based on their approach to letter coding: the first two use open bigrams, the second two use approximate slot-based coding and the last uses spatial coding.

SERIOL (Sequential Encoding Regulated by Inputs to Oscillations within Letter units; Whitney, 2001) was developed specifically to address the phenomenon of relative-position (RP) priming. It was the first model to use open-bigram coding (Grainger &

Whitney, 2004) in which both the adjacent and non-adjacent letters of a word are converted into ordered pairs (e.g., the word *cat* would be represented by the open-bigrams *ca ct at*).

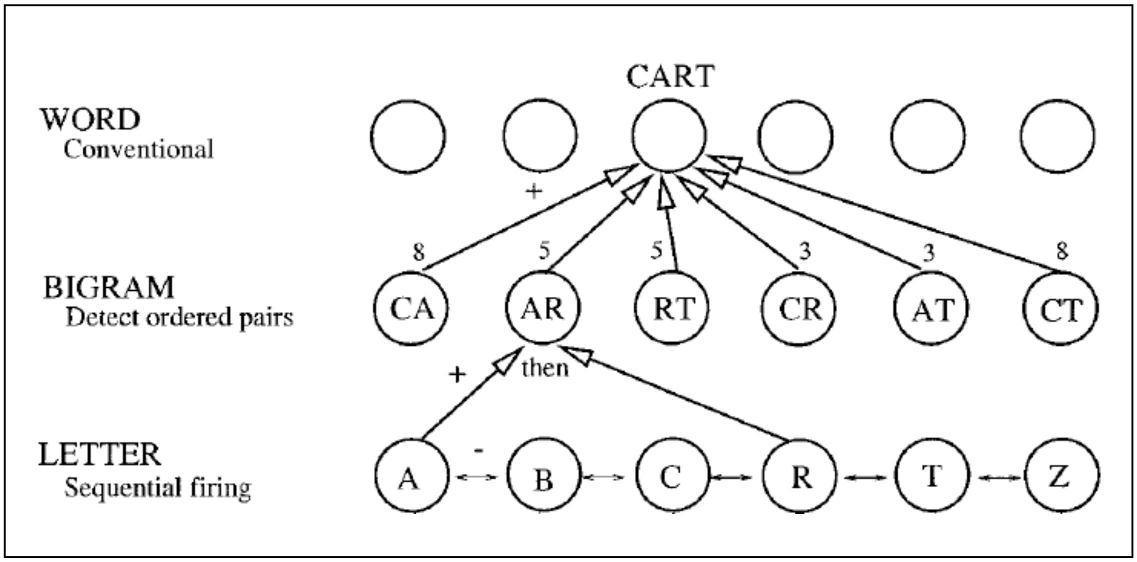

FIG. 2: The open-bigram coding mechanism (taken from Whitney, 2001)

Relative letter position is maintained by the serial and sequential firing of individual letter units but absolute order information is lost. The open-bigrams are continuous across the entire word but greater weight is given to those formed from contiguous letters. There is also a locational gradient of activation that is highest for the first letter and decreases across the word. The updated version of the model (Whitney & Cornelissen, 2008) includes edge units that explicitly encode the first and last letters of words as many studies have indicated that they exert a greater influence than interior letters in word recognition (e.g., Forster, 1976; see Jordan, Thomas, Patching, & Scott-Brown, 2003, for a review).

An open-bigram coding system is also central to the discrete open-bigrams model (Grainger & van Heuven, 2003) but this uses a discrete weighting system to ensure that bigrams formed with fewer than two intervening letters are given a weight of 1 and those formed with more than two intervening letters are given no weight; this model therefore has a greater emphasis on local context than SERIOL. The conversion of letters into bigrams occurs in parallel across the word. In both SERIOL and discrete open-bigrams a location-invariant representation of the letters is created; in the former this is implemented in the temporal firing of the letter units whereas in the latter each letter has a separate representation for each retinal location creating a spatial array. In an extension of this model (the Overlap Open-Bigram model; Grainger et al., 2006) the weighting system was modified to give a lower activation value to bigrams composed of non-adjacent letters up to the two letter limit.

A different approach has been to use the basic slot-based system of the IAM (McClelland & Rumelhart, 1981) but add Gaussian noise to increase flexibility, a system known as ‘slots plus slop’ (Davis & Bowers, 2004) that was implemented in the overlap model (Gómez et al., submitted). It contains letter detectors whose receptive fields overlap into the neighbouring slots. The identification of a letter in a particular position leads to an increased probability that it is also identified in the surrounding positions, with the probability diminishing with increasing distance from the original letter according to a Gaussian function.

In contrast, the split-fovea theory of word recognition (Shillcock et al., 2000) reduces the number of slots to only two, one for either side of the fixation point. Given the precise splitting of the human fovea along the vertical meridian (see Brysbaert, 2004, for evidence) the letters in each slot are processed by the contralateral hemisphere without further ordering (Shillcock et al., 2000). Despite the extremely distributed nature of this system (i.e., only two sets of letter input units are activated across each whole word) it uniquely accounts for 98.6% of words in the CELEX English database (Baayen, Pipenbrock, & Gulikers, 1995) and the addition of a special role for exterior letters allows for unambiguous recognition of 99.81% of words. A variation of this model contained eight slots (four per hemisphere) in order for researchers to be able to present four-letter words at every possible fixation position during the training regime, from the entire word falling in one hemisphere to a split of the letters across the two (Monaghan, Shillcock, & McDonald, 2004; Shillcock & Monaghan, 2001). This allows it to overcome both the alignment problem (Bowers, 2002) that occurs in models unable to recognise familiar words when presented in an atypical position, and to an extent the dispersion problem (Plaut et al., 1996) of not applying the letter-phoneme correspondence learned in one position to letters in a different position. The split-fovea model naturally reproduces the exterior letters effect due to the hemispheric division of labour caused by the foveal split: over repeated presentations the exterior letters develop a stronger exclusive relationship with one hemisphere (the first letter with the right hemisphere and vice versa) than do any other letters, and thus preservation of the correct position of the exterior letters is more important than for interior letters (Shillcock & Monaghan, 2001).

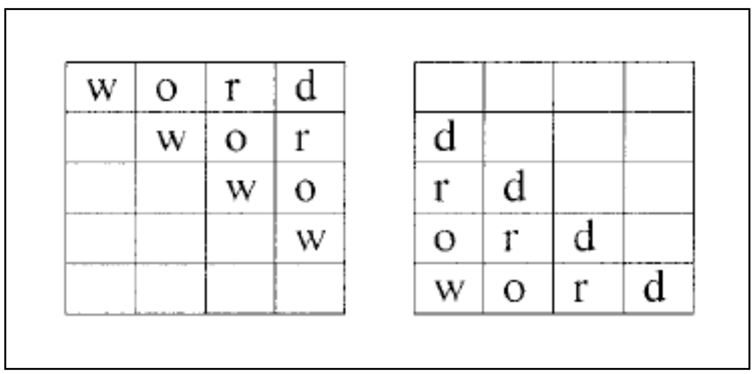

FIG. 3: The multiple fixations training regime of the split-fovea model (taken from Shillcock & Monaghan, 2001)

Finally, the notion of spatial coding underpins the SOLAR model (Davis & Bowers, 2006). As in earlier models letter position and identity are simultaneously coded but in this model it is the relative order of letters within the word that is specified by the relative activation level of letter units. So, if the input is *dog* then the letter unit for *d* would be most activated, followed by *o* and then *g*. A match value for the pattern overlap between this spatial orthographic code and the spatial code for each whole-word detector unit is calculated, and the word detector with the highest match value is selected.

Models of word recognition: Distinguishing between recent models

Which of these models is most successful at capturing the TL and RP priming data described above? At first glance they all represent an improvement over slot-based coding and wickelfeatures. TL and RP primes share many of the same contiguous and non-contiguous open bigrams as the target word, and their spatial coding provides a similar match value to that of the target word, thus explaining the success of SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003) and SOLAR (Davis & Bowers, 2006) at explaining these effects. Similarly, the overlap model (Gómez et al., submitted) provides an account of TL effects, at least when transpositions are of adjacent letters. Unfortunately, little work has been done assessing the suitability of the split-fovea model (Shillcock & Monaghan, 2001) in this area; discussion of this model will be deferred until the end of the section.

In order to distinguish between these models several studies have carried out explicit comparisons of their ability to explain more subtle effects. Davis and Bowers (2006) contrast the predictions made by SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003) and SOLAR about the similarity of word pairs such as *soap* and *stop* in which one letter is transposed and one substituted (TS pairs). The identical weighting of contiguous and non-contiguous bigrams in the discrete open-bigrams model (Grainger & van Heuven, 2003) leads to a prediction of identical levels of priming from TS and SL primes. SERIOL (Whitney, 2001) predicts, counter-intuitively, more priming from TS primes than SL primes as there is increased weighting of both contiguous bigrams and the initial letters in a word; thus, it cannot distinguish between letters that are contiguous but at the end of a word and letters that are non-contiguous but at the start of a word. In a masked priming experiment comparing TS and

SL primes the outcome of a faster lexical decision to a target word following an SL prime was only correctly predicted by SOLAR.

Although Davis and Bowers (2006) did not explicitly test the predictions of the overlap model (Gómez et al., submitted) they concluded that it is counterintuitive to employ a position-specific coding scheme and then add noise to make it fit with data that clearly imply relational coding of letters, and they note that it is subject to the alignment problem mentioned above (*cat* and *pole* not recognised as part of *catpole*; Bowers, 2002). Additionally, they tested the concept of a locational gradient in SERIOL (Whitney, 2001) by comparing primes whose transpositions and substitutions were towards either the start or end of the prime, but no difference in lexical decision response times between these conditions was recorded. Grainger et al. (2006) also found no support for the importance of exterior letters in SERIOL (Whitney, 2001) in their experiments, with no advantage for primes in which the position of one or both exterior letters was maintained.

Consideration of the importance of exterior letters formed the basis of the extreme transpositions priming investigated by Guerrera and Forster (2008). They compared exterior letters primes (13254768) with interior letters primes (21345687) and found that they were both less effective than an identical prime condition and more effective than an unrelated letters control. Correctly positioned exterior letters are neither sufficient to equal the priming levels produced when all of the letters of a target word are matched, nor necessary for priming to occur. In order to test whether priming from exterior letters is solely due to the correct placement of the initial letters they created two contrasting exterior letters conditions in which either the initial or final letter pair of the target word was the only one that was not transposed. The results imply support for the increased weighting of initial letter bigrams in SERIOL (Whitney, 2001). However, this cannot be fully substantiated as although the initial letters condition provided priming compared with an unrelated control, and the final letters condition did not, there was no statistical difference between them. Lastly, a 'Reversed Halves' condition (43218765) produced no priming, a finding not predicted by SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003) or SOLAR that all predict some orthographic overlap with the target word. This result led the authors to conclude that none of these models provides sufficient local context information to constrain the most extreme TL effects.

The issue of serial versus parallel processing of letters was considered by Whitney and Cornelissen (2008) in their comparison of SERIOL (Whitney, 2001) and the discrete open-bigrams model (Grainger & van Heuven, 2003). At the letter level of SERIOL (Whitney, 2001) activated letter units fire serially at a rate of about 15 milliseconds per letter producing an abstract temporal location-invariant representation of letter order. This representation is spatial in the discrete open-bigrams model (Grainger & van Heuven, 2003), with horizontally presented letters presented in parallel by an alphabetic array of character detectors. Whitney and Cornelissen (2008) argue that SERIOL's serial processing perfectly explains the finding by Peressotti and Grainger (1995) that primes formed by re-arranging all three letters of a target word produced increased priming after exposure durations increasing from 33 to 50 to 67 milliseconds. After 33 milliseconds, only one of the abstract letter units of the target word would be activated, after 50 milliseconds two would be activated, and after 67 milliseconds all three would be activated, leading to the observed monotonic increase in priming levels, although intuition suggests that increasing the exposure duration of the prime leads to increased levels of priming simply due to the generally increased time available for processing the prime. Further support for SERIOL comes from Whitney (in press) who claims that under new parameters it predicts more priming from SL than TS primes, matching the prediction by SOLAR (Davis & Bowers, 2006) and the data recorded by Davis and Bowers (2006).

As mentioned above, there has been little discussion of the split-fovea model (Shillcock & Monaghan, 2001) in the priming literature. Davis and Bowers (2006) mention it in passing but claim that it suffers from the same drawbacks as other slot-based models such as the IAM (McClelland & Rumelhart, 1981) and cannot account for TL effects.

However, Shillcock and Monaghan (2004) confirmed that the model is able to reproduce the TL word pair interaction demonstrated in the human naming latency data by Andrews (1996), as the higher frequency member of a TL pair (e.g., *calm*-*clam*, high frequency-low frequency) tended to require a longer response time than would be predicted on the basis of its frequency (so *calm* would require a longer response time than *clam*). The critical difference between the split-fovea model (Shillcock & Monaghan, 2001) and other slot-based models is that although its input depends upon the absolute position of letters its training regime presents every word in every potential fixation position. Thus, in order for successful word recognition the model must recognise every letter in a word in multiple positions and associate those difference positions with one word output.

For example, if the model is trained on the word *walk* it will process *w* in letter input positions 1-5, *a* in positions 2-6, *l* in positions 3-7 and *k* in positions 4-8 (see Figure 3). If it is then presented with the novel TL prime *wlak* the model will have seen the letters *l* and *a* in these transposed positions during its training, and so the prediction is that a TL non-word will be more likely to prompt the model to settle on the target word as an output than an SL prime such as *wutk* (as with all connectionist models this is dependent on the lexicon it accumulated during training). The process of letter association is aided by the information bottleneck created by the restricted hidden units between the input and output layers that force the model to learn the regularities and patterns in the training data. However, if the amended letters include the exterior letters a prime is less likely to induce the model to produce the target word as no letter other than the first and last will have been presented to slots 1 and 8 respectively (see Figure 3) and any resemblance to the target word will require more mediation from the hidden units. This specific prediction remains to be tested in the model's output to TL and SL primes involving exterior and interior letters.

In conclusion, comparisons between recent models have provided mixed results and there is no clear 'front-runner' at present. Key differences between them include the issue of seriality, the importance of exterior letters and their responses to extreme transpositions.

Eye-movements in reading: Oculomotor influences

The literature review until this point has focused on the descriptions of orthographic processing put forward in models of isolated word recognition. However, the vast majority of word processing is in the context of other words during text reading, and it is to the parallel subject of the modelling of eye movements during reading that this review now turns. The study of the eye movements that occur during reading has flourished over the past 30 years; current thinking is that the primary factors guiding fixation positions and durations are visual and linguistic information respectively. In this section I will give a brief description of the characteristic eye movement pattern observed during reading and subsequently present the evidence underpinning firstly oculomotor and then cognitive models.

Reading is characterised by a series of fixations, typically lasting around 200-250 milliseconds, separated by rapid eye movements known as saccades that are on average 7-9 letter spaces in length. It is generally agreed that eye movements occur in order to allow the word of interest to be projected onto the fovea, the 2° of central vision where acuity is greatest. Mapping of the distribution of fixations that fall on a word produces a normal distribution centred on a point slightly to the left of the middle (the preferred viewing location; Rayner, 1979). This differs from the optimal viewing location (OVP; O'Regan, 1992) that is defined for isolated words as the fixation point located towards the centre of a word at which word identification is most rapid.

While it seems to the reader that fixations typically occur on every word and saccades travel from left-to-right across a line of text (at least for left-to-right orthographies) this pattern is punctuated by regressive eye movements and re-reading of previously seen material and words are often skipped over altogether. Approximately 10-15% of eye movements are regressions and about 1/3 of words are skipped; the probability of regressions increases when the text is complex and the probability of word skipping increases when words are frequent and short. The word currently being fixated is known as word n, with the preceding word known as word n-1 and the following word known as word n+1. The 5° of visual area surrounding the fovea on either side is called the parafovea, with the word to the right of fixation in a left-to-right language typically referred to as the parafoveal word. Most of the interest in this topic has been on the position and duration of the fixations (‘where’ and ‘when’), although the causes of regressions and skipping have received attention. Language researchers typically use eye-tracking cameras to directly record and measure the eye movements made while participants read words or sentences presented on a computer screen, a method that allows for detailed scrutiny of every movement made.

Jerry is usually quite grouchy until he has had his morning coffee and read the paper.

Fixations	*	*	*	*	*	*	*	*	*	*	*	*	*
Order	1	2	3	4	5	7	6	8	9	10	11	13	12
Duration (ms)	311	218	266	202	182	233	178	193	215	227	233	145	288

FIG. 4: A typical pattern of eye movements (taken from Starr & Rayner, 2001)

The measures employed when quantifying eye movement patterns vary according to the unit of analysis. If lexical access is of interest then first-pass measures are typically considered, as they represent forward fixations made on initial reading prior to a saccade out of the word. These include first fixation duration, which is the duration of the first fixation on a word regardless of the number of subsequent fixations, and gaze duration, which is the sum of the durations of all fixations made on first-pass reading. Single fixation duration is measured when only one fixation occurs during first-pass reading. When text integration and re-reading are being considered then measures such as total time (the sum of all fixations on the word of interest regardless of regressions) are appropriate. For more detail of the pattern of eye movements the number of regressions out of a word or the probability of word skipping can be more informative.

One of the clearest sources of information that could be used to control where the eyes move is low-level visual and oculomotor factors such as word shape and length, and the launch distance from the previous word. These factors are obvious candidates for predicting eye movements and account for much of the variance observed in fixation positions. For example, McConkie, Kerr, Reddix, and Zola (1988) analysed the initial fixation positions of a large number of words and found that they could be modelled along five purely oculomotor principles. Fixation position is primarily determined by launch position with any variation around the landing site accounted for by the systematic tendency for the eyes to overshoot or undershoot in saccade length and by the random error caused by perceptual-oculomotor variability. Further analysis of these data by Reilly and O'Regan (1998) shows that the simple heuristic strategy of targeting fixations towards the longest word in a 20-character window to the right of the current fixation can give a good approximation of the landing-site distribution residuals reported by McConkie et al. (1988).

Eye-movements in reading: Low-level models

This emphasis on the importance of oculomotor factors over cognitive factors was modelled by O'Regan (1990) in the Strategy-Tactics model. When the eyes approach a new word this framework initially uses the strategy of directing the eyes to the 'generally optimal' viewing point of a new word (just to the left of centre). However, if the eyes fall too far outside of this area the model employs the rescue tactic of moving the eyes to the opposite side of the word from where it landed. Although the timing of the second of two fixations and long single fixation durations can be influenced by lexical factors the model gives oculomotor effects a much larger role to play than cognition. Another model largely reliant upon low-level sources of information is the ideal-observer Mr. Chips model of Legge, Hooven, Klitz, Mansfield, and Tjan (2002). It is a quantitative model that provides a good simulation of some eye movement behaviours with an input that includes only low-level informational constraints. The model exploits three sources of information in its decision making: visual (whether letters are present or absent on the 'retina'), lexical (relative word frequencies) and eye movement accuracy (the probability of making an eye movement error). The optimising principles that underpin the model ensure that this information is used to execute a saccade of the length that is most likely to allow identification of an upcoming word. The authors suggest that the entropy-minimising strategy for planning saccades implemented in Mr. Chips mirrors human saccade-control heuristics.

In a similar vein, the SERIF model (McDonald, Carpenter, & Shillcock, 2005) explicitly eschewed the consideration of lexical input in order to assess how much eye movement variance can be accounted for without it. The model differs from others in its inclusion of the bisection of the human fovea. This split is implemented using two decision-making units that are contralaterally connected and whose output is a signal that increases over time at a constant rate. A race between these two units to be the first to reach a threshold indicating a saccade determines the model's decision to implement a saccade. The numerical parameters of several reading mechanisms estimated using the Dundee reading corpus (Kennedy, 2003) are implemented in the two units by adjusting the intercept and slope of the signal increase rate. Following exposure to the corpus, they found that the model produced eye movement behaviours that mimicked features of human reading in several important ways, including the word frequency effect and the trade-off between the durations of first and second fixations.

The limitations of word-based guidance strategies (see Cognitive influences below) was highlighted by Yang and McConkie (2004) in their demonstration that removal of word boundaries during reading does not affect saccade initiation and length: if the eyes are always guided by the upcoming word (as indicated by a word boundary) then reading should be impaired when boundaries are absent. Specifically, single fixation replacement of word spaces in text with random letters did not alter saccade activity levels for the first 175 msecs or so of presentation, and many saccades took place as normal after this period. Their proposed Competition/Interaction (C/I) theory (Yang & McConkie, 2001) does not give words a critical role to play in saccade generation but rather assumes that saccades are initiated after a random waiting time. Cognitive factors such as reading strategy and processing difficulties can act to influence the general saccadic activity level, but only if the saccade is delayed for more than about 325 msecs do cognitive factors have direct inhibitory control over saccade initiation; early saccades are not affected by cognitive processing at all.

Eye-movements in reading: Cognitive influences

The models of eye-movement control during reading discussed so far have focused primarily on the role of low-level factors in determining where the eyes move across text. There is some additional evidence that low-level factors, particularly word length, also affect the amount of time spent fixating a word (O'Regan, 1990). However, more recently there has been an acknowledgement that these low-level processes cannot account for all of the control of eye movements, particularly for the more flexible variable of fixation durations (see Starr & Rayner, 2001).

This is principally a problem for models such as SERIF (McDonald et al., 2005) that formulate oculomotor explanations for effects that are readily accounted for by linguistic factors. For example, the choice of the next word to be fixated by SERIF is made by random sampling from the cumulative probability distribution of words n+1 to n+3, with the parameters of this distribution guided by the word object properties of these words such as length; however, the frequency of an upcoming word is a well-established factor in determining whether it is skipped or not (see Brysbaert, Drieghe, & Vitu, 2005). It seems counterintuitive to design a model that does not refer to lexical variables when their explanatory power is evident. Indeed, even partial word information is sufficient to guide eye movements (Lima & Inhoff, 1985). Additionally, the assumption in the Strategy-Tactics model (O'Regan, 1990) that fixation position is a key determinant of fixation duration is based on responses to words presented in isolation in which if the eyes fall on a non-optimal position processing time is extended (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984): this processing cost is largely eradicated during reading (Vitu, O'Regan, & Mittau, 1990).

Researchers instead turned to observations of eye-movements to infer underlying cognitive processing of text (see Rayner, 1998) and based more recent models on the accumulating evidence that several 'higher order' lexical, syntactic and discourse-level features influence fixations, such as word frequency, predictability and syntactic class (e.g., Binder, Pollatsek, & Rayner, 1999; Henderson & Ferreira, 1990; Rayner & Duffy, 1986; Rayner & Raney, 1996; Rayner & Well, 1996). For example, Rayner, Sereno, and Raney (1996) found an effect of lexical frequency on the duration of both the first and second fixations across words of multiple lengths, a finding in direct contrast to the predictions of the Strategy-Tactics model (O'Regan, 1990). However, they do acknowledge that a hybrid model might be the most effective in predicting eye movement behaviour.

Eye-movements in reading: The role of attention

During the accumulation of evidence that low-level factors are not sufficient to explain control of eye movements there was the simultaneous discovery that parafoveal words are pre-processed prior to an eye movement towards them. Any information gleaned during the preview of an upcoming word in parafoveal vision is integrated into lexical access when the word is subsequently fixated; this is known as parafoveal preview benefit (Rayner, 1998) and it leads to decreased processing time for the previewed word i.e., reduced fixation durations. This benefit was originally discovered using studies of isolated words (e.g., Rayner, McConkie, & Ehrlich, 1978) but researchers quickly realised the implications of this finding for models of reading (e.g., Inhoff & Tousman, 1990).

Parafoveal preview benefit in reading is typically studied by comparing the fixations on a target word when, prior to fixation on the target word, different preview stimuli had been presented at the target location using the boundary technique (Rayner, 1975). As shown in Figure 5, an invisible boundary is inserted into the text immediately before the target word. Until the eyes reach the boundary the preview word is displayed, but as soon as the eyes cross the boundary the preview word is changed to the target word and fixations on the post-boundary word are analysed. The shortest fixations on the post-boundary word are found when the preview word is identical to the post-boundary word with parafoveal preview benefit compared to an unrelated preview usually in the order of 20-50 milliseconds reduction in fixation durations. Comparison of the fixation durations in different preview conditions (see Figure 5) gives an indication of how much information is extracted from parafoveal words.

This line of reasoning has fruitfully been followed through with many studies reaching a consensus in several areas. It is widely agreed that pre-lexical and lexical information is extracted during parafoveal preview. For example, Rayner (1975) found that fixations on the post-boundary word were reduced when the preview had the same word shape and exterior letters as the post-boundary word, but word and non-word previews were only distinguishable when the last fixation prior to the boundary was less than six characters from the start of the post-boundary word. Balota, Pollatsek, and Rayner (1985) found that participants spent less time inspecting the post-boundary word when the preview stimulus was orthographically similar. They also noted the interaction between visual similarity and predictability: visually similar previews had a greater influence when they were similar to a predictable target word. In a related study, White, Rayner, and Liversedge (2005) showed that predictability only affected post-boundary fixation durations when the word length of the preview was correct. Both phonological (Pollatsek, Lesch, Morris, & Rayner, 1992) and partial-word (Inhoff & Tousman, 1990) similarity between the preview and post-boundary word can provide a processing benefit, although the presence of word-initial letters does not constrain the set of lexical candidates for the post-boundary word (Lima & Inhoff, 1985).

```
The cat jumped when the| dog growled              (identical)
                      * |
The cat jumped when the| fuy growled      (related word shape)
                      * |
The cat jumped when the| doy growled (orthographically related)
                      * |
The cat jumped when the| ape growled          (unpredictable)
                      * |
The cat jumped when the| fox growled     (semantically related)
                      * |
The cat jumped when the| dog growled          (post-boundary)
                          *
```

FIG. 5: Five different parafoveal preview conditions and the post-boundary presentation of the target word *dog*; the dashed line indicates the position of the invisible boundary and the asterisks indicate the position of the eyes

More controversial is the possibility of semantic pre-processing of words. While Underwood and colleagues (e.g., Hyönä, Niemi, & Underwood, 1989; Underwood, Clews, & Everatt, 1990; Underwood, Clews, & Wilkinson, 1989) found that fixations were more likely to fall in the more informative half of a parafoveal word, Rayner, Balota, and Pollatsek (1986) found that a semantically related preview word provided no more facilitation than an unrelated preview. Similarly controversial is the possibility of parafoveal preview benefit from word n+2, rather than word n+1. Rayner, Juhasz, and Brown (2007) presented sentences with a boundary paradigm and concluded that there was no evidence for a preview benefit from word n+2, whereas a repetition of this work by Kliegl, Risse, and Laubrock (2007) showed the opposite effect.

If word n+1 is being processed (and therefore attended to) while the eyes are still fixated on word n, the question arises as to how to characterise the link between eye movements and the allocation of attention during reading. This question has led to a split in the class of models that describe eye-movement control as contingent upon lexical processing into two types. One group views processing as linear, with attention shifting between words in a strictly serial manner that is not necessarily directly linked to the position of the eyes. These models are known as sequential attention shift (SAS) models, in which attention and therefore lexical processing is confined to one word at a time so that lexical processing of an upcoming word can only happen after the lexical processing of the current word is complete (e.g., Morrison, 1984; Reichle, Rayner, & Pollatsek, 2003). The second group claims that attention is spread across several words around the fixation point (guidance by attentional gradient, or GAG models); thus, orthographic and lexical processing occurs in parallel across several words at a time (e.g., Engbert, Longtin, & Kliegl, 2002; Reilly & Radach, 2003). I will outline details of the key models exemplifying these two groups below, along with critical evidence distinguishing between them.

Eye-movements in reading: Morrison's model (1984)

An early proponent of serial processing was Morrison (1984) who introduced a model of eye movement control driven by lexical access that included serial attention shifts and parallel programming of saccades. Once processing of the current word is completed attention shifts to word n+1 and when attention has been allocated to word n+1 for a criterion amount of time this automatically signals the preparation of a saccade, although this is not initiated immediately due to a programming latency. The inclusion of attention in the model explains how parafoveal preview benefits are possible, as an upcoming word is processed during the lag between the shift of attention to that word and the initiation of a saccade towards it. Where the saccade ultimately takes the eyes is determined by the interactions between multiple saccades that are programmed in parallel. This enables the model to account for several findings from the reading literature, including the routine occurrence of word skipping: if word n+1 is short or frequent it can be processed before the criterion time to initiate a saccade towards it is reached. Attention thus shifts to word n+2, with the effect that the saccade that is initiated is directed to word n+2 and word n+1 is simply skipped.

Despite its highly influential nature several essential problems with the Morrison model (1984) were quickly identified. One of its predictions was that the level of parafoveal processing should be independent of foveal processing load. However high the processing load of the foveal word (due to its infrequency or unpredictability) this cannot affect processing of word n+1 due to the fixed time for parafoveal pre-processing that elapses between the shift of attention to word n+1 and the initiation of a saccade towards it. Linked to this was its lack of an explanation as to why high foveal load words are re-fixated: simply put, the model did not take into account the importance of foveal processing load. Both of these issues were addressed by the proposal that foveal and parafoveal processing levels are co-dependent (Henderson & Ferreira, 1990). They manipulated foveal load to assess its effect on parafoveal preview benefit for the upcoming word by comparing fixation times across sentences in which the foveal word was either low or high frequency. They found that parafoveal preview benefit for visually similar previews compared with visually dissimilar previews was reduced when foveal load was high. They suggested the addition of an eye movement programming deadline such that if foveal processing is very time-consuming, an eye movement is initiated after a certain period of time regardless of whether attention has yet shifted and thus parafoveal preview benefit is reduced. This has the additional benefit of providing a mechanism for re-fixations within a word as the eye movement initiated could fall within the same word if processing of this word was not completed.

However, this deadline, although parsimonious, was not strictly necessary according to the description of the model given by Morrison (1984), as he makes almost no assumptions about what causes attention to shift to word n+1 or about what affects the length of time that elapses before a saccade is initiated. It is therefore possible that the existing framework allows for the interaction of foveal and parafoveal load: for example, increased difficulty of processing word n could lead to a reduced lag between attention shifting to word n+1 and execution of an eye movement without requiring a deadline mechanism. On this point, Kennison and Clifton (1995) extended the work of Henderson and Ferreira (1990) and presented participants with sentences containing a high or low frequency foveal and parafoveal word to assess the impact of these frequencies on parafoveal preview benefit and fixations on the parafoveal word. Importantly, they analysed the distribution of single fixations on the foveal word, as a fixation deadline would predict that fixations on low frequency words have a cut-off maximum duration. They instead found that the distributions were continuous for both the high and low frequency words, and thus concluded that a different mechanism is required to account for the effect of foveal load on parafoveal preview benefits. Prefiguring future work in this area, they proposed an uncoupling of attention from saccade execution (Reichle, Pollatsek, Fisher, & Rayner, 1998) and even suggested that attention might in fact be distributed over more than one word at a time (Engbert et al., 2002).

Eye-movements in reading: E-Z Reader

The first solution presented by Kennison and Clifton (1995) for the question of how foveal and parafoveal words interact was utilised by Reichle et al. (1998) in their introduction to the E-Z Reader model. This was the first of several papers laying out the evolution of the model as although its central ideas have remained it has undergone several modifications. Despite the authors' statement that it is a model of how lexical processing affects eye movements, and that they will not attempt to simulate either syntactic/discourse-level findings or letter-level fixation positions, it has been hugely influential in generating work in the field of reading research. It is considered to be one of the most complete models of eye movement control during text reading.

E-Z Reader is explicitly based on the Morrison model (1984), with serial lexical processing and parallel programming of saccades. According to the Morrison model, a shift of attention to word n+1 triggers a simultaneous eye movement but in E-Z Reader the crucial improvement is the de-coupling of attention from saccade initiation that provides a mechanism for the interplay of foveal and parafoveal processing (as suggested by Henderson & Ferreira, 1993). This is achieved in a two-step word recognition procedure: an initial familiarity check on word n triggers an eye movement to word n+1, and subsequent lexical access of word n causes a shift of attention to word n+1. It is assumed that there is a fixed amount of time that elapses between the initiation and execution of a saccade, so that whenever attention shifts to word n+1 before the saccade is completed preview of word n+1 occurs. However, if the processing time required for lexical access of word n exceeds this fixed saccadic execution time an eye movement towards word n occurs before the shift of attention, leading to ‘spillover’ from word n to word n+1 (Rayner & Duffy, 1986). Parafoveal preview benefit is therefore dependent on the ease of lexical access for word n, bringing the model in line with the findings of Henderson and Ferreira (1990) and Kennison and Clifton (1995).

Reichle et al. (1998) outlined 5 instantiations of the E-Z Reader model, and at each step a new feature was added to improve its fit and psychological plausibility. E-Z Reader 1 simply describes the sequencing of events in a typical fixation, based on the eye movement and attention shift steps outlined above, both of whose mean durations are a function of the frequency of the fixated word. The eye movement itself is composed of three parts: a labile stage of saccade planning that could be cancelled by parallel processing of a subsequent saccade; a non-labile stage of saccade planning; and the actual saccade itself. If attention on word n shifts to word n+1 during the labile stage of the eye movement to word n+1, and the familiarity check on word n+1 is completed during this labile stage, this then triggers an eye movement to word n+2 that will cancel the ongoing eye movement to word n+1, causing word n+1 to be skipped altogether.

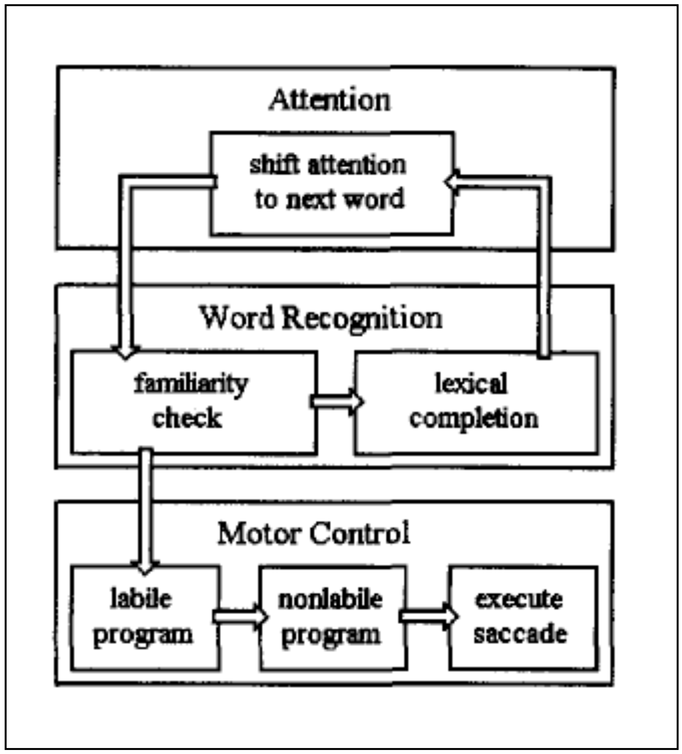

FIG. 6: The component processes of E-Z Reader 1 (taken from Reichle et al., 1998)

In E-Z Reader 2 word predictability information is added by reducing the duration of both steps for more predictable words. E-Z Reader 3 allows for multiple fixations on the same word by setting up an intra-word mechanism identical to the inter-word mechanism except that it is triggered immediately upon fixation within a word; these intra-word fixations are cancelled by completion of the familiarity check i.e., the triggering of an inter-word saccade. Thus, the cessation of an earlier saccade by a later one is the mechanism responsible for both cancelling refixations and skipping. By stating that refixations will always occur on the attended rather than the fixated word, this provides an account of regressions caused by incomplete lexical access of word n when word n+1 is being fixated. E-Z Reader 4 incorporates an eccentricity function to make parafoveal processing less efficient than foveal processing, whereas E-Z Reader 5 distinguished the parafoveal processing style from the foveal processing style by slowing the more fine-grained lexical processing stage more than the cruder familiarity checking stage for parafoveal word processing only. E-Z Reader 5 provides an admirable estimation of the observed data (taken from the corpus collated by Schilling, Rayner, & Chumbley, 1998) for several fixation duration variables as well as skipping and fixation probability variables for five frequency groups of words.

One area in which E-Z Reader was still deficient was identified by Reichle, Rayner, and Pollatsek (1999) who noted the model's inability to make predictions about where the eyes land at the letter level as E-Z Reader 5 only predicts word skipping and regressions. In contrast, the landing-site distribution data recorded by McConkie et al. (1988) were closely approximated by Reilly and O'Regan (1998) using a simple oculomotor strategy. As discussed above, McConkie et al. analysed the causes of saccadic error and concluded that they are due to both systematic error causing the eyes to overshoot near targets and undershoot distant ones, and random oculomotor error. E-Z Reader 6 incorporated these two types of error by assuming that all saccades aim for the OVP but added overshoot or undershoot of 0.4 characters for saccades shorter or longer respectively than seven characters, plus random error. This new model was trained by adding word length information to the original Schilling et al. (1998) corpus; it was able to produce a good approximation of the landing position distributions and refixation distributions recorded by McConkie et al. and Rayner et al. (1996) respectively while maintaining its reliance on linguistic processing and ability to simulate fixation duration patterns.

A model that followed the main principles of E-Z Reader but with the remit of modelling the more general link between cognition and eye movements was EMMA (Eye Movements and Movement of Attention; Salvucci, 2001). Salvucci discusses two major flaws of models of visual processing, namely that they assume that a shift of fixation equals a shift of attention, and that object processing times are independent of the properties of the object, flaws that are not present in E-Z Reader. While EMMA therefore retains some of E-Z Reader's key features such as the decoupling of overt eye movements from covert shifts of attention and the modulation of processing by eccentricity it incorporates several amendments to increase its domain-independent applicability to cognition. One difference is that where the eyes land is determined by a Gaussian distribution around the centre of the object, rather than by systematic and random error around the optimal viewing location as is the case in E-Z Reader. Another is that when cognition requires attention to shift to a new object, encoding of that object is initiated simultaneously with an eye movement to the new object as EMMA does not know the next saccade target object until directed by cognition. Its generalisation from lexical processing to cognition allows EMMA to capture effects from non-linguistic visual processing domains such as visual search while retaining the ability to model word frequency effects.

Later versions of E-Z Reader (versions 7-9) focused on testing the model and refining its ability to simulate eye movement patterns. Reichle et al. (2003) introduced two amendments to the architecture of E-Z Reader 6. The first was the addition of an early visual processing stage prior to the familiarity check (now labelled stage L1, with full lexical access labelled L2) covering the pre-attentive transmission of information from the retina to the visual cortex. This low-spatial frequency information identifies gross features in peripheral vision such as word boundaries and the presence of ascenders/descenders, information that is then used by the oculomotor system to programme saccades and by higher-level visual mechanisms to focus the serial attentional 'spotlight'. The second was the elimination of the automatic within-word re-fixation mechanism, as within-word re-fixations are instead initiated with a probability related to the length of the word to be fixated. This allows the model to correctly predict that long words are more likely to receive additional fixations than short words. These amendments brought the model's simulation of word processing times more in line with actual findings on the probability of fixations and fixation durations. When the model was 'lesioned' so that the familiarity check could only start after the word was fixated to simulate word recognition without parafoveal preview, the cost for processing times was similar to that seen experimentally. E-Z Reader 7 also maintained the ability of E-Z

Reader 6 to make letter-level fixation position predictions comparable to those measured by McConkie et al. (1988).

Finally, Pollatsek, Reichle, and Rayner (2006) and Reichle, Pollatsek, and Rayner (2006) discuss how E-Z Reader makes accurate predictions for both naturalistic reading and more unusual experimental text presentations. One example they present is the disappearing text paradigm showing that when word n disappears after 60 milliseconds reading rates remain virtually unchanged but when both word n and word n+1 are removed reading slows by approximately 30% (Rayner, Reichle, & Pollatsek, 2005). E-Z Reader simulated this effect by producing much longer fixations on word n+1 when it had disappeared after fixation on word n than when word n alone had disappeared because 76% of the time the model shifted its attention to word n+1 only after it had disappeared and so it received no parafoveal preview of word n+1. The authors claim that this suggests that 60 msecs is the time required to 'fix' visual information from a word so that it can be lexically processed without any further visual input, but only if attention has been allocated to that word. The disappearing text finding can therefore be explained by a serial lexical processing model that has not allocated attention to word n+1 at the time of its disappearance, thus causing a disruption in processing when it is removed.

This support for serial shifts of covert attention causing lexical processing to proceed one word at a time is one of the key elements of the E-Z Reader framework (and the other serial processing models discussed above). Apart from its beneficial consequences when modelling paradigms such as disappearing text, the main theoretical reason given by the authors for its support is that it allows the reader to maintain word order (Reichle et al., 2003). Readers encounter words one-by-one in the correct order, identify them, and integrate them into the text, before moving their attention on to the next word. Attention in this case is defined as the selection of a word for processing, involving the integration of its visual features to allow word identification to take place (Rayner & Pollatsek, 1999). In E-Z Reader terms, once lexical access (L2) of word n has been completed attention shifts to word n+1 and the familiarity check (L1) of word n+1 begins (in E-Z Readers 7+ this happens after the pre-processing has finished). This insistence on strictly serial processing has been a major source of conflict within the reading research community, and recently a set of effects, known as parafoveal-on-foveal effects, have emerged that are presented by advocates of parallel lexical processing as seriously undermining any models reliant on attention-shifting (e.g., Kennedy & Pynte, 2005).

Parafoveal-on-foveal effects: Early work

As mentioned above, a model as well-specified as E-Z Reader is bound to attract scrutiny, and much of this has been directed towards its assertion that lexical processing is serial in nature. The alternative is to allow parallel processing of text to occur, with more than one word processed simultaneously. Two predictions that arise from a model claiming parallel processing of text are foveal-on-parafoveal influences (the effect of the processing of word n on the processing of word n+1) and parafoveal-on-foveal influences (the effect of the processing of word n+1 on the processing of word n; Underwood, Binns, & Walker, 2000). The first of these predictions has been widely demonstrated in the documentation of spillover effects (Rayner & Duffy, 1986) and the modulation of parafoveal processing by foveal load demands (e.g., Henderson & Ferreira, 1990). It was incorporated into E-Z Reader without requiring parallel lexical processing as the independence of eye movements and attention shifts leads to demanding processing of word n reducing or even denying attention to word n+1. However, the existence of parafoveal-on-foveal effects is not easily explained by serial processing models that assume that lexical processing of word n+1 (or occasionally word n+2) can only commence after lexical processing of word n has been completed. Parafoveal-on-foveal effects are seen as a clear test of whether there is serial or parallel processing of a line of words in text (Drieghe, Brysbaert, & Desmet, 2005) and it is therefore the second of these predictions that I will concentrate on.

Early work in this area (pre-dating E-Z Reader) by Henderson & Ferreira (1993) appeared to show that there was no effect of parafoveal processing on the processing of word n. They presented participants with sentences containing three designated words. Word one was an initial word, and the processing load of words two and three was manipulated using frequency, and frequency plus length plus syntactic class, respectively. They analysed the effects of words two and three on first-pass reading measures for words one and two, and found no effect of the upcoming word on the fixated word i.e., no parafoveal-on-foveal effects. However, they did not control the properties of word one despite their own previous finding that when foveal load is high parafoveal processing is reduced (Henderson & Ferreira, 1990), nor did they include first fixation duration or number of refixations as outcome variables in their analyses, both of which have since been shown to index parafoveal-on-foveal effects (e.g., Kennedy, 1998).

The existence of parafoveal-on-foveal influences was therefore dismissed until Kennedy (1998, 2000) re-started research into this topic, research that has since led to a flurry of similar studies. Kennedy's choice of paradigm was motivated by the desire to exert more control over fixations than occurs in normal reading while retaining eye-movement dynamics and lexical processing. He (Kennedy, 1998) therefore used a 'looks-means' task in which three words were presented to the participant, the first of which was a 'prompt' word indicating the type of judgement to be made of the second two words. If the prompt was 'looks', the judgement was of the orthographic similarity of the following two words, whereas if the prompt was 'means', the judgement was of semantic similarity. For example, if the word triplet was *looks sand send*, the response would be positive. In both cases, the prompt word acted as the target word and the first word of the pair acted as the parafoveal word. Kennedy found shorter gaze durations on the prompt word were recorded when the parafoveal word was long and had an uninformative initial trigram. There was no effect of parafoveal word frequency, although there was a trade-off between time spent on the prompt word and time spent on the parafoveal word suggesting that at least sub-lexical processing is distributed.

However, analysing responses to the prompt word that is presented multiple times throughout the experiment is not optimal, and it would be more convincing to analyse the effects of the second word of the target pair on the first.

Kennedy (2000) instead used two versions of a ‘clothing search’ task in which participants had to search for a rare occurrence of a clothing word in a display of three words. Experiment 1 presented these search words at a fixed point, while in Experiment 2 participants had to first look through a display of z’s before a boundary change prior to the three words. He found a complex interaction between lexical and sub-lexical variables. For example, parafoveal word length was inversely related to foveal processing time for parafoveal words with uninformative initial trigrams and there were shorter foveal inspection times when short parafoveal words had informative trigrams. In Experiment 1, gaze durations increased when the parafoveal word was of high frequency. Kennedy suggested that this data show that attention is more widely distributed across the visual field than is allowed for by serial attention switching models.

The possibility of a higher-level pragmatic parafoveal-on-foveal influence was investigated by Murray and Rowan (1998) and Murray (1998) who employed a same/different sentence matching paradigm in which participants judged the physical similarity of two sentences. Despite this task requiring a seemingly low-level comparison Murray and Rowan state that it in fact requires syntactic and semantic processing as it is faster to make a single comparison based on a higher-level sentence representation than to make multiple comparisons based on the individual words of each sentence. The sentences were of the structure noun1-verb-noun2, and in the target sentence (always the first of each pair) the plausibility of the relationship between the nouns and the verb was manipulated. For example, in the sentence *The vicar corrected his giant* the first noun-verb pairing is plausible while the second is not. They found that when the noun1-verb pair was implausible, the duration of the last fixation on noun1 increased, although this was only true when the last fixations on noun1 fell on the latter part of the word. These data are particularly meaningful as they show the immediate nature of pragmatic influences even in a task in which they are not required for success.

Parafoveal-on-foveal effects: Criticisms and responses

Naturally, criticism of this work was quickly forthcoming from those who advocated serial processing. Rayner, White, Kambe, Miller, and Liversedge (2003; also Rayner & Juhasz, 2004; Rayner, Pollatsek, & Reichle, 2003) laid out three major drawbacks with the studies claiming to have demonstrated parafoveal-on-foveal effects: the use of artificial tasks, the inconsistent findings and the absence of lexical effects, particularly frequency effects. However, each of these criticisms has since been answered by recent experiments, and I will outline each criticism and its response in more detail below. Their first criticism was of the use of artificial tasks, such as the looks-means task (Kennedy, 1998) or the same/difference sentence matching task (Murray & Rowan, 1998), which are not good approximations of natural reading but rather more similar to visual search. However, this point had already been addressed by Inhoff, Starr, and Shindler (2000) who had instead used sentences containing an invisible boundary to investigate orthographic and semantic parafoveal-on-foveal effects. This paradigm and the four experimental conditions are shown in Figure 7.

Baseline Preview Condition:

He approached the yellow traffic light with some caution.
*
He approached the yellow traffic light with some caution.
*

Uppercase Preview Condition:

He approached the yellow traffic LIGHT with some caution.
*
He approached the yellow traffic light with some caution.
*

Dissimilar-Letter Preview Condition:

He approached the yellow traffic qvtqp with some caution.
*
He approached the yellow traffic light with some caution.
*

Inconsistent-Context Preview Condition:

He approached the yellow traffic smoke with some caution.
*
He approached the yellow traffic light with some caution.
*

FIG. 7: The four post-boundary word conditions (taken from Inhoff, Starr, et al., 2000)

They found both orthographic (*light* vs. *qvtqp*) and visuospatial (*light* vs.*LIGHT*) effects of the post-boundary word on first-pass reading measures and total reading time on the pre-boundary target word, and post-boundary word meaning affected reading times when fixations on the target were close to the boundary. In an even more ecologically valid experiment, Underwood et al. (2000) presented participants with passages whose last sentence contained a noun phrase that was sometimes the anaphoric referent of an item described earlier in the passage. This noun was followed by a word that had either an informative or redundant initial trigram. This allowed for an orthogonal manipulation of both foveal load (as the anaphoric noun phrase was easier to process) and parafoveal load (the informative trigram rendered word n+1 easier to process). They found that first fixation durations on the target word were shorter when either the target word load was low or, crucially, when parafoveal load was high.

The second concern voiced by Rayner, White, et al. (2003) was the lack of consistency in the findings of parafoveal-on-foveal effects, both from experiments that have reported null findings and in the type of effects that have been reported. For example, White and Liversedge (2004) found no effect on fixation durations or re-fixation rates on word n when word n+1 contained a misspelling of its initial trigram. Similarly, in the Rayner et al. (1986) study reported above investigating semantic parafoveal preview benefits, an additional analysis of the gaze durations on the pre-boundary word found no effect of word n+1. Although both Underwood et al. (2000) and Kennedy (2000) showed that the informativeness of the initial trigram of word n+1 affects fixations on word n, these effects were in the opposite direction. In order to try to disentangle the often complicated and contradictory nature of parafoveal-on-foveal findings, Hyönä and Bertram (2004) collated their eye-tracking data from five previous experiments to assess the impact of parafoveal word frequency on the fixated word. Unfortunately, they did not succeed, as across the five experiments there were both conflicting and nonsignificant effects of word n+1 frequency on gaze duration.

Kennedy, Pynte, and Ducrot (2002) discuss these ‘embarrassing’ discrepancies that they attempted to elucidate by controlling five potential sources of variance including the length and frequency of both the foveal and parafoveal words and the informativeness of the initial trigram of the parafoveal word, again using eye-tracking during a 5-word ‘clothing search’ task. Their findings illustrate the impact of experimenters’ choice of foveal and parafoveal stimuli when designing experiments. When both the foveal and parafoveal word are long, acuity constraints mean that there are no effects of parafoveal informativeness or frequency. When the foveal word is short, gaze durations are reduced when there is a low frequency parafoveal word with an informative initial trigram, as the trigram limits the lexical choices for the infrequent parafoveal word; the same is true for fixations falling in the second half of a long foveal word. For fixations falling in the first half of a long foveal word there is instead a tendency to re-fixate within the word, and when the foveal load is high parafoveal-on-foveal effects are greatly diminished. Although these results were complicated they do not indicate that parafoveal-on-foveal influences are inconsistent but rather that the length and frequency of foveal and parafoveal stimuli determine the outcome of experiments.

Since this work, experimenters have been increasingly careful to control for these factors and a variety of studies have demonstrated sub-lexical and lexical parafoveal-on-foveal effects. Starr and Inhoff (2004) found both orthographic and lexical effects in sentence reading with increased first fixation and gaze durations on the pre-boundary word when the post-boundary stimulus was either a random string of letters or an orthographically legal nonword. Vitu, Brysbaert, and Lancelin (2004) presented participants with pairs of words that were either orthographically unrelated or high-low frequency orthographic neighbours that differed by either an external or internal letter. Not only were single fixation and gaze duration on the first word reduced when the second word was related, but the effect of letter position substitution was modulated by word frequency as fixations durations were reduced for low frequency words only by external letter similarity and reduced for high frequency words only by internal letter similarity. Kennedy, Murray, and Boissiere (2004) not only replicated the pragmatic effects of Murray (1998) but also found long-range effects of the initial trigram token familiarity of noun2 on noun1 in sentences with a noun1-verb-noun2 structure. Kliegl et al. (2007) found that both first fixation and gaze durations on word n were increased when word n+1 was a content word.

The third criticism of Rayner, White, et al. (2003) concerns the elusive nature of lexical parafoveal-on-foveal effects. They pointed out that when parafoveal-on-foveal effects are found, they tend to be sub-lexical effects only. In the context of a debate about serial versus parallel processing, Rayner and colleagues argued that sub-lexical parafoveal-on-foveal effects are not necessarily problematic for models such as E-Z Reader that are dependent on the serial allocation of attention. When E-Z Reader 7 was introduced by Reichle et al. (2003) it included the novel feature of a pre-attentive early visual processing stage that allows for parallel processing of low-level visual features across more than one word. This processing could in principle explain the orthographic irregularity effects found by Inhoff, Starr, et al. (2000) and Starr and Inhoff (2004) as unusual letter combinations present in parafoveal vision might stand out and affect eye movement behaviour without requiring a shift of attention. From a neurological perspective, the presence of unusual upcoming information is likely to be coded in a saliency map located in the superior colliculus that determines the next location to be attended (e.g., Itti & Koch, 2000). It should be noted that they do not explain why Inhoff, Starr, et al. and Starr and Inhoff recorded increased foveal fixation times when illegal letter combinations were present in the parafovea, even though unusual letter combinations are actually more likely to attract attention and shorten foveal processing times.

As Rayner and colleagues admit, lexical parafoveal-on-foveal effects are more difficult to reconcile with a serial attention-shifting model, but as mentioned above they contend that they are too elusive to pose a serious threat. This is exemplified in the very mixed findings of Hyönä and Bertram (2004). In particular, they cite the null findings of Schroyens, Vitu, Brysbaert, and d'Ydewalle (1999) and Altarriba, Kambe, Pollatsek, and Rayner (2001) that are all the more surprising given the robust nature of foveal frequency effects (Rayner, 1998). Schroyens et al. primarily investigated parafoveal preview benefit in a three-word 'clothing search' task and found that the frequency of the parafoveal word had no effect on single fixation durations on the target word, although they did not analyse any other variables such as gaze duration. Interestingly, the authors concluded that their work supported the concept of parallel processing due to findings such as the modulation of parafoveal preview benefit by the frequency of the parafoveal word itself. Altarriba et al. analysed Spanish-English bilinguals reading sentences containing a variety of orthographically and semantically related preview words that were either in the same language as the rest of the sentence or in the alternative language. Fixation durations on the pre-boundary word were identical whether the preview word was in the same language or not, providing no evidence for lexical parafoveal-on-foveal effects. However, both this experiment and the former employed rather unnatural tasks, as the latter required mid-sentence translation and the former used the ‘clothing search’ task whose use by Kennedy (2000) had previously been criticised by Rayner and colleagues.

In an attempt to prove that parafoveal-on-foveal effects are robust, researchers turned to examining eye movement corpora for evidence of parallel processing (Kennedy & Pynte, 2005; Kliegl, Nuthmann, & Engbert, 2006; Pynte & Kennedy, 2006). The typical finding was of both pre-lexical (initial letter informativeness) and lexical (frequency) influences. Following a large study involving over 200 participants reading a variety of sentences, Kliegl et al. presented evidence for the ubiquity of distributed processing. They carried out repeated-measures multiple regression analyses (Lorch & Meyers, 1990) to test the effects of frequency, length and predictability of the previous, current and upcoming word on first-pass fixations on the current word. Single-fixation durations on word n were reduced with an increase in the frequency of word n+1, but only when word n was short. In contrast, fixation durations on word n increased with an increase in the predictability of word n+1, but only when word n was long; this was despite a typically positive correlation between word frequency and predictability. Additionally, there was often a cognitive lag whereby processing of word n-1 continued during fixation of word n, as shown by the effects of predictability and frequency of word n-1 on word n.

This study (and the use of corpora in general) was criticised by Rayner, Pollatsek, Drieghe, Slattery, and Reichle (2007) who suggested that Kliegl et al.’s small regression coefficients only attained significance due to the increased power of their data. They also pointed out the discrepancy between the findings from single fixation and gaze durations, with any parafoveal-on-foveal findings much attenuated when using the latter measure. Single fixations are unlikely to be representative of the whole data set as they involve the exclusion of very short or long words that are likely to be skipped or re-fixated respectively. Kliegl (2007) replied with a re-analysis of the 2006 data using a 79-predictor linear mixed-effects regression analysis that showed that regression coefficients for the lag and successor effects were consistent across nine samples each consisting of a moderate number of subjects and so could not be due to large sample sizes only. Kliegl concluded by suggesting that future work combine findings from three sources of information, namely experiments, models and corpus regression analyses.

Even if lexical parafoveal-on-foveal effects can be consistently demonstrated using natural reading tasks, Rayner, Juhasz, et al. (2007; also Drieghe, Rayner, & Pollatsek, 2008; Rayner, Warren, Juhasz, & Liversedge, 2004; Rayner, White, et al., 2003) have one final suggestion for how parafoveal-on-foveal effects do not necessarily spell the end for serial lexical processing of text. They claim that parafoveal-on-foveal findings are more likely to be mislocated fixations (Nuthmann, Engbert, & Kliegl, 2005) such that although the eyes are fixated on word n, it is word n+1 that it being processed. Nuthmann et al. derived an algorithm for calculating the number of mislocated fixations during reading by extrapolating out from the number of fixations on the foveal word to those that would have fallen on a neighbouring word using a Gaussian fixation distribution, and comparing the probability of fixating on a neighbouring word with that of fixating on the foveal word. This led to a figure of approximately 10% mislocated fixations, a figure that Rayner and colleagues claim is sufficiently high to account for the significant findings of parafoveal-on-foveal influences. They predicted that, if this is the case, any parafoveal-on-foveal findings should be independent of the frequency of word n (as this is not the word undergoing processing) and that they should only occur when the eyes are close to the parafoveal word. These predictions were borne out in a replication of the work by Inhoff, Starr, et al. (2000) showing that there was a significant increase in single fixation durations on word n when word n+1 contained an orthographically illegal initial trigram only for fixations within three characters of word n+1 (Drieghe et al., 2008).

However, this point had already been discussed by several studies. Inhoff, Radach, Starr, and Greenberg (2000) presented readers with sentences containing a target word plus a post-target word that was either a repetition of the target, semantically associated with it, or unassociated. They found reduced first-fixation and gaze durations when the target and post-target were related compared with when they were unassociated; separate analyses of those fixations that fell on the last four characters of the target word and all other fixations yielded identical results. Starr and Inhoff (2004) carried out a similar partition of their data: increased first fixation and gaze durations on word n when word n+1 was a random letter string occurred even when fixations falling on the final two letters of word n were removed from the dataset. Pynte and Kennedy (2006) pointed out that the pattern of results from their English and French corpus work, involving two languages and both lexical and pre-lexical effects, suggests that these parafoveal-on-foveal influences are unlikely to be due to calibration error from mislocated fixations.

Several theories have been proposed to account for how the properties of parafoveal words are able to affect foveal word processing. These can be split into two groups, the distributed processing theories and the purely parallel theories. An example of the former is the ‘Visibility Hypothesis’ of Kennedy and colleagues (Kennedy, 2000; Kennedy et al., 2002; Pynte & Kennedy, 2006; also Drieghe et al., 2005) that explains their complex findings with a process-monitoring mechanism to allocate processing resources depending upon the difficulty of adjacent words. For example, Kennedy (1998) found a negative correlation between the time spent on word n and the time spent on word n+1 and proposed that words n and n+1 are processed in parallel with saccadic eye movements serving to optimise visibility. Similarly, Hyönä and Bertram (2004) posit a theory that short, low frequency words in the parafovea provide a ‘magnetic attraction’ of the eyes away from foveal processing. This is well exemplified in the work of Pynte, Kennedy, and Ducrot (2004) who showed that typographical errors at the start of post-boundary words, that were explicitly set up as an area of magnetic attraction, influenced fixations on the pre-boundary word.

The purely parallel theories instead propose that attention is allocated to adjacent words as well as the fixated word and that the spread of attention is limited only by acuity. Based on their previous findings, Starr and Inhoff (2004) described the attention-gradient hypothesis in which processing of the parafoveal word is at the expense of processing of the foveal word and therefore fixation durations on the foveal word are increased. Vitu et al. (2004) also interpret their findings as indicating purely parallel processing with simultaneous letter processing and no role for attention. They found that the presence of an orthographic neighbour in parafoveal vision reduced foveal fixation durations, but critically the effect of letter position substitution interacted with word frequency such that parafoveal-on-foveal effects were larger for low frequency foveal words when the parafoveal orthographic neighbour differed from the target word by an exterior letter. This is difficult to reconcile with a distributed processing model that would always allocate more attention to the low frequency word and thus reduce the impact of altering parafoveal information. Whichever theory is correct, the conclusion to this section is clear: parafoveal-on-foveal effects provide strong evidence for some form of parallel processing across multiple words, and so it is to models of parallel processing of text that this review now turns.

Parallel processing models

The second far-sighted proposal by Kennison and Clifton (1995) to explain the interaction between foveal and parafoveal processing was that attention could be distributed over more than one word at a time. A recent model reliant upon parallel processing of this kind is the SWIFT model of Kliegl and colleagues (Saccade-generation With Inhibition by Foveal Targets; Engbert et al., 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005; Richter, Engbert, & Kliegl, 2006). SWIFT is based on the core principle that processing of lexical information is spatially distributed over four words at a time (words n-1 to n+2) with lexical processing following a positively skewed Gaussian distribution (see Figure 8).

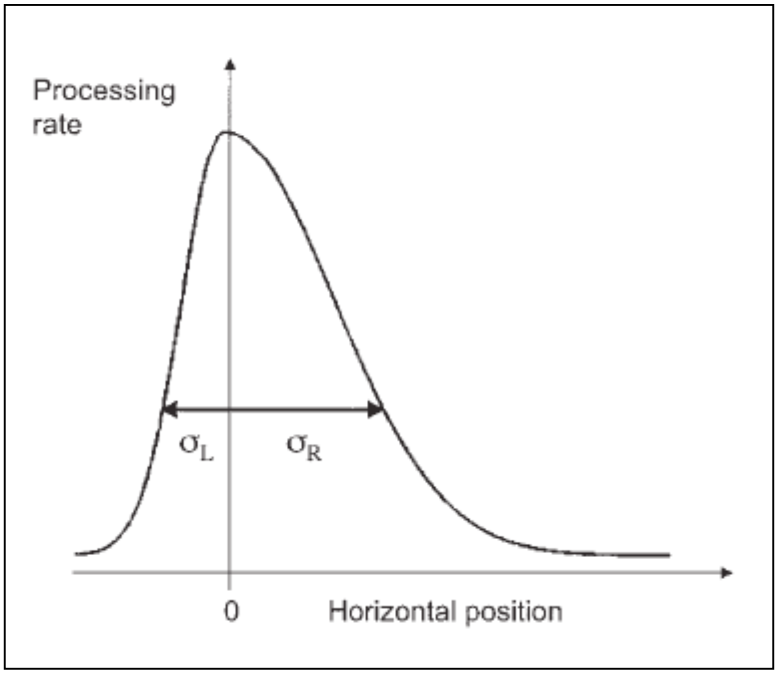

FIG. 8: The lexical processing rate distribution in SWIFT (taken from Engbert et al., 2005)

There is a parallel build-up of activation across these words and the one with the highest level of activation at the time of saccade generation is selected as the target of that saccade. Saccades are generated autonomously and occur partly to maintain a particular rate of eye movements, but this is not a purely autonomous process as it is modulated by the difficulty of the foveal word: if foveal lexical activation is too high, a saccade will not occur. Some of the mechanisms implemented in SWIFT are similar to those of E-Z Reader (e.g., Reichle et al., 2003). In both models saccades have both a labile and non-labile stage, and in SWIFT selection of the saccade target comes at the end of the labile stage. Lexical processing also occurs in two stages of lexical access and completion, with lexical access speeded by increased word frequency and predictability, and a visual acuity gradient is in operation.

These principles give the model a common mechanism for forward and backward saccades including refixations and word skipping, and allow the model to account for parafoveal-on-foveal effects and the finding that information can be detected from the left of fixation (e.g., Inhoff, Radach, et al., 2000). The choice of a saccade target based on a lexical access competition explains both word skipping and refixations, as if a word has already achieved lexical access its activity is low and it is not selected, and if a currently fixated word is proving difficult to access its activity will be high and it is likely to be re-selected. In order to allow for a direct comparison with E-Z Reader, SWIFT's performance on reading measures was compared with the human data in the Schilling et al. (1998) reading corpus. This model is able to reproduce basic effects of word frequency and predictability on fixation durations, skipping and refixation rates. Interestingly, the 'dumb' mechanism of autonomous saccade generation is largely sufficient, with inhibition by foveal targets only occurring about 15% of the time. SWIFT is also more accurate in its simulation of moderately increased fixation durations (approximately 20 milliseconds longer) prior to a skipped word, which falls in line with the human data (e.g., Pollatsek, Rayner, & Balota, 1986) unlike E-Z Reader in which the cancellation of the saccade produces a long delay (173 milliseconds for E-Z Reader 5; Reichle et al., 1998).

Richter et al. (2006) introduced a letter-level refinement to the processing gradient and an account of the systematic errors that are observed in landing distributions (McConkie et al., 1998). In the amended model the speed of processing a letter depends on its eccentricity from the point of fixation due to acuity limitations. This produces a letter processing span that follows a positively-skewed Gaussian curve. The systematic landing distribution errors are explained by the system's preference for saccades of a certain length, thus causing undershoots in saccades longer than this and overshoots in saccades shorter than this preferred length, and random error also increases with the length of the intended saccade. These adjustments allow SWIFT to more accurately reproduce initial landing site distributions. This includes the counter-intuitive Inverted Optimal Viewing Position effect (IOVP; Nuthmann et al., 2005) that fixation durations are longer when the fixation falls on the middle of a word than at its edges. Under a SWIFT framework this occurs because fixations falling at the edge of a word are in fact mislocated and a saccade to a more optimal viewing position is rapidly initiated. A point to note is that although Rayner and colleagues (e.g., Rayner, White, et al., 2003) claim that these mislocated fixations are responsible for parafoveal-on-foveal effects this is not the case in SWIFT in which attention and eye movements are not de-coupled and attention is simply centred on the mislocated fixation.

A model that follows many of the principles of SWIFT is Glenmore (Reilly & Radach, 2003, 2006). This places even more reliance on parallel processing and competition between simultaneously activated lexical representations. It is a connectionist model composed of layers of processing units feeding into a "fixate centre" whose activation level falling below a threshold level triggers a saccade. Saliency units determine the target of the saccade based on the word with the highest activation level. The only lexical-level processing in the model is of word frequency implemented in the word units: the value of the self-recurrent connections in the word units is determined by the word's frequency, with the activation level of higher frequency words rising more rapidly. They also have inhibitory connections to other words to simulate word competition, allowing words to be processed in parallel but with one word dominating the competition for resources.

Glenmore is able to account for several basic findings, at least in a qualitative manner. Spill-over and preview effects come from the activation values of the previous word being carried over to the next. The dynamic processing of words accounts for the preview benefit of upcoming words and dynamic interactions between words account for the foveal modulation of preview benefit. Refixations occur when the currently fixated word wins the word resource competition, and regressions similarly occur when a previous word becomes the most salient. Quantitative simulations showed that there is a reasonable match for the effects of word length and frequency on fixation durations, and also for landing distributions. Reilly and Radach (2006) also discuss the differences between SWIFT and Glenmore that include SWIFT's 2-stage lexical processing compared to Glenmore's use of letter-level processing, and SWIFT's reliance upon lexical processing levels to determine saccade target selection compared with Glenmore that allows the more complex interplay of visual and linguistic factors for saccade target selection.

Comparisons between the models

As might be expected, several studies have made direct comparisons between these models' abilities to simulate various reading variables. Due to the recent accumulation of work on parafoveal-on-foveal effects most of these comparisons have focused on the debate concerning serial versus parallel processing, with E-Z Reader and SWIFT most often the subjects of comparison. For example, Reichle et al. (2003) compared the performance of E-Z Reader with that of other models, in particular those advocating parallel lexical processing, and acknowledged that they are serious contenders. Similarly, Engbert et al. (2005) presented a serial processing version of SWIFT and discussed how there might be a continuum rather than a dichotomy between the two positions. However, both sides provide evidence to support their respective positions, evidence that is outlined below.

The main theoretical argument presented by Rayner and colleagues in defence of serial processing is that it allows for easy first-pass encoding of word order (Reichle et al., 2003), particularly for a language such as English in which word order is a guide to meaning. From a neurophysiological perspective, Pollatsek et al. (2006) noted that the human brain evolved to understand spoken language, which is intrinsically serial. Parallel models would have difficulty in encoding word order without an unparsimonious additional mechanism. They also question the implementation of the attentional gradient, as if it is too shallow then parallel models predict too much processing of upcoming words. However, if the gradient is then increased parallel processing models become almost indistinguishable from serial models.

There is also experimental evidence that parallel models would have difficulty explaining. The disappearing text paradigm employed by Pollatsek et al (2006) and Reichle et al. (2006) demonstrated the disruption in reading produced when both word n and n+1 vanished 50 milliseconds after fixation on word n (this stands in contrast to the disappearance of word n only, following which reading proceeds largely as normal; Rayner, Liversedge, White, & Vergilino-Perez, 2003). This result is easily explained by an attentional spotlight that had not yet been directed at word n+1 at the time of disappearance, while if attention was allocated to both word n and word n+1 at the time of disappearance this parallel processing system would predict minimal processing disruption even when both word n and word n+1 disappeared. Another prediction from parallel processing is that there should be some parafoveal preview benefit for word n+2, although this was not borne out experimentally (Rayner, Juhasz, et al., 2007, although see Kliegl et al., 2007). Lastly, despite the evidence for parafoveal-on-foveal influences presented above, critics (e.g., Rayner, White, et al., 2003) maintain that these do not serve to disprove that lexical processing is serial in nature.

Advocates of parallel processing have several replies to these points. As mentioned above, Engbert et al. (2005) described how SWIFT can be used to model both serial and parallel processing by varying the number of words under consideration for both the pre-processing and lexical completion stages. Interestingly, when lexical completion was restricted to one word at a time the number of words undergoing pre-processing actually increased compared to when there were no restrictions; it was simply that the lexical completion stage was delayed. Inhoff, Starr, et al. (2000) pointed out that in E-Z Reader this delay leads to a discontinuity in processing of word n+1 in cases in which lexical processing of word n is ongoing but early visual processing of word n+1 is complete. Word n+1 enters a stage of 'waiting-for-attention' with its lexical and semantic processing being delayed until it is fixated. Inhoff, Eiter, and Radach (2005) addressed this prediction experimentally by delaying the presentation of a target word until the pre-target word was fixated. Parafoveal preview benefit from presentation of the target word compared to a pseudoword preview was identical whether the identical preview was available for only the first 140 milliseconds after fixation on the pre-target word or only from 140 milliseconds onwards. In other words, linguistic processing of word n+1 is not restricted to the latter part of a fixation on word n. This is incompatible with the strict segregation of linguistic processing between words implemented in E-Z Reader.

In reply to the point about parafoveal-on-foveal effects, answers to the various criticisms are presented above, and the acceptance of parafoveal-on-foveal effects is now widespread. This is literally the case in the work by Kliegl et al. (2007), who pointed out that the lack of parafoveal preview benefit for word n+2 reported by Rayner, Juhasz, et al. (2007) was probably due to their use of short words for word n (increasing the probability of their being skipped) and long words for word n+1 (so that word n+2 fell outside the perceptual span). Once these flaws were removed Kliegl et al. found parafoveal-on-foveal effects from both word n+1 and word n+2.

Finally, on a more philosophical note, Kennedy (2003) argued that the assumption that lexical processing in reading follows the same pattern as lexical processing of speech is a fallacy. Reichle et al. (2003) refer to word order as temporal, invoking the link with spoken language, whereas reading instead involves sampling across a spatial array that is constantly available for pre- and re-processing. Kennedy and colleagues (e.g., Kennedy, 1992; Kennedy & Murray, 1987) formalised this notion that text reading involves spatial representation of text in the 'spatial coding' hypothesis. They demonstrated that participants were able to make accurate large regressive saccades during sentence reading, implying that they must have a spatial representation of the preceding text. This provides a mechanism for maintaining word order without strictly serial processing of words. It appears that the pendulum of scientific opinion is currently swinging away from serial processing and its restrictive qualities, towards a model of eye movement control during text reading involving the distribution of attention across more than one word at a time in which the interaction between foveal and parafoveal word characteristics is usual and potentially useful.

Relationship between isolated word recognition and eye-tracking measures

This literature review has firstly discussed the orthographic input to models of isolated word recognition and then moved on to look at the evidence for parallel processing of words in text, but has so far treated these as separate topics. This is not an error: researchers also tend to confine themselves to one area or the other, and historically there has been little overlap as it is widely assumed that the same lexical effects demonstrated in isolated word recognition also underpin the processing of words in text. Therefore, the process of word recognition in models of text reading has typically remained vague or relied on the design of an existing word recognition model for its details. Given that models of word recognition are often designed to simulate the findings from specific isolated word processing paradigms this use is questionable (Radach & Kennedy, 2004). For example, the IAM (McClelland & Rumelhart, 1981) was specifically designed to simulate the word superiority effect. There are also additional sentence- and text-level influences present during reading that models of isolated word recognition are not required to account for. This review is not the place for a complete discussion of this topic but in this section I will present evidence from the increasing number of studies that explicitly compare the effects found using eye-tracking, lexical decision and naming tasks, as a starting point for the refinement of word recognition modules in text reading models.

Of course, as both isolated word recognition and text reading require lexical processing there will be some variables that impact both tasks. An obvious candidate is word frequency, as the decreased response time to higher frequency words in isolation stems from their repeated use in text. Empirically, faster responses to higher frequency words were first demonstrated in a lexical decision task by Rubenstein, Garfield, and Millikan (1970) and in a naming task by Forster and Chambers (1973). Similarly, fixation durations are reduced for higher frequency words as shown by eye-tracking of isolated words by Rayner (1977) and words in sentences by Rayner and Duffy (1986). However, these separate experiments do not allow for comparison of the size of the effects or type of stimuli used, and so a direct comparison is preferable.

The first study to carry out this comparison was by Schilling et al. (1998) who compared naming, lexical decision and silent sentence reading, with identical high and low frequency words as the target for analysis in each. They found that the frequency effect was correlated across participants for lexical decision latencies, naming latencies and gaze durations, but first fixation durations did not correlate with lexical decision or naming. Naming latencies and fixation durations were more strongly correlated on response times to high and low frequency words and overall response times than when either of these tasks was compared with lexical decision times, but the overall correlation between lexical decision times and fixation durations was still significant. This suggests that there is a common lexical access component to the three tasks. Juhasz, Starr, Inhoff, and Placke (2003) extended this work by separately assessing the frequency effect for the first and second lexemes of compound words such as *piecemeal* (high-low) and *patchwork* (low-high). All three tasks showed that the frequency effect was more pronounced for the second lexeme, implying that compound words are decomposed into their constituent parts when they are presented singly and in context.

Turning next to orthographic effects, Perea and Pollatsek (1998) found that a larger orthographic neighbourhood slowed lexical decision times for low-frequency words with at least one higher frequency neighbour compared to those with no neighbours. However, when these words were embedded in a sentence there was no effect of frequency on first-pass measures e.g., first fixation duration. Instead, the probability of regressions to the target word was twice as high when it had higher frequency neighbours, and there was an increase in the processing time of the target word and post-target region, with these effects once again stronger for low-frequency words. The conclusion from both experiments was that the effect of higher frequency neighbours is to inhibit lexical access, particularly in its later stages. Johnson, Perea, and Rayner (2007) reproduced the transposed-letters effects discussed towards the start of this review in a reading task comparing the parafoveal preview benefit received from TL and SL neighbours of the post-boundary word. This finding is all the more important because it potentially excludes slot-based coding as an input system in models of eye movement control during text reading in the same way it has largely been discounted in isolated word modelling techniques.

The role of phonology in word ambiguity was demonstrated with converging evidence from naming, silent reading and oral reading by Folk and Morris (1995). Three types of ambiguous words were presented in a context that was appropriate to the subordinate meaning: the words had multiple meanings (*bank*), multiple meanings and pronunciations (*tear*; heterophones) or multiple meanings and multiple spellings (*sale*; heterographs). There was initial processing difficulty (indexed by first-pass fixation measures) on the heterophones only and participants made more regressions to these words, naming latencies were slower and more errors were produced when naming heterophones, and answers to the comprehension questions asked after the oral reading task showed that the incorrect version of the ambiguous word was chosen more often after the heterophones. These results all suggest that multiple phonological codes are active and compete during integration of words into text, adding a layer of interference and complexity to the resolution of ambiguous words. Pollatsek et al. (1992) showed that phonology is also a key type of information that is integrated across saccades in both isolated word priming and in parafoveal preview benefit. They recorded a 20 millisecond decrease in response time when homophones were used as the prime or parafoveal preview in a naming task or silent reading task respectively, compared to a visually similar control word. These experiments exemplify the many factors that have been shown to affect responses to both isolated words and words in context.

However, it would be surprising if the task demands of reading had no impact on the word recognition process. The typical finding is that effects that seem clear-cut for single words are attenuated for words presented in context. Any differences recorded could be due to a) the low-level motor and visual systems employed during reading, b) the peculiarities of isolated word recognition tasks, and c) the increased higher-level processing required during reading. Starting with the first of these points, a potential low-level factor is the fixation point on a target word. O'Regan (1992) determined that the Optimal Viewing Position (OVP) where recognition is fastest falls just to the left of the centre of an isolated word, yet systematic analysis of landing positions for words in context showed that the Preferred Viewing Location (Rayner, 1979) is actually further to the left of centre. Clearly, what is optimal for single words has to be re-considered when the reader is faced with multiple words in sequence and when the experimenter is not controlling their fixation points. A similar constraint falls on words in the parafovea that are pre-processed but without the benefits of foveal vision. Although the evidence for a privileged role for exterior letters pairs in isolated word processing is abundant (for a review see Jordan Thomas, Patching, & Scott-Brown, 2003), there is some controversy over whether or not the presence of the final letter in a parafoveal word provides any parafoveal preview benefit (Inhoff, Radach, Eiter, & Skelly, 2003; for a reply see Jordan, Thomas, & Patching, 2003). Any decreased role for the final letter in a parafoveal word is likely due to the lower visual acuity in peripheral vision.

Moving on to the second potential source of differences between isolated words and text, researchers have noted that the tasks used to determine that word recognition has occurred have their own demands that might index different aspects of the lexical access process. For example, Inhoff, Briihl, and Schwartz (1996) found that silent reading produced the opposite result from on-line and delayed naming tasks in a study of morphemic structure and word processing. In the former, first fixation durations were increased for compound words; in the latter, compound words were named faster than mono-morphemic and suffixed controls. They suggested that the meanings of both parts of a compound word are activated and that while this is beneficial in a naming task as both parts contribute to lexical activation this is detrimental in reading in which one meaning, that of the overall word and not its constituents, is required. They concluded that naming and first fixation durations index different aspects of word recognition, with the former being sensitive to the first part of lexical processing and the latter sensitive to later stages of lexical processing. In their study on the effects of word frequency across different tasks, Schilling et al. (1998) found that the lexical decision task was more sensitive to lexical frequency effects than naming or reading as low frequency words take a long time to distinguish from non-words.

One reason for the attenuation of these effects is the third point mentioned above, that there are additional effects of the surrounding words that come into play during reading and that act to reduce the relative importance of word-level effects. These come both directly from flanking words and indirectly from higher-level semantic, syntactic and discourse-level variables. Features of the previously fixated word can be seen in spillover from word n-1 to word n, with a low-frequency word inflating fixation times for the next word (Rayner & Duffy, 1986). In contrast, the parafoveal pre-processing of words that is possible during reading reduces the amount of processing that is required when words are fixated, providing a benefit that is not available for words in isolation. A higher-order variable that is very prevalent in text is the predictability of a word from its preceding context, which serves to reduce fixation probability and durations for very predictable words (Ehrlich & Rayner, 1981). A related variable is transitional probability, the measure of the likelihood of co-occurrence of two words that might serve as an independent source of predictability information (McDonald & Shillcock, 2003a, 2003b; see Chapter 7).

In conclusion, there is increasing recognition that, in order for models of eye movement control during text reading to advance, there is a need to integrate findings from the isolated word literature to help constrain the letter and word recognition process that is commonly a 'black box' in the text-level models (Radach & Kennedy, 2004). This criticism has been levelled at E-Z Reader in particular, as its two-stage word recognition process has been described as poorly or inaccurately specified and contrary to current knowledge of the variables that affect single word recognition (e.g., Andrews, 2003; Hyönä & Bertram, 2003). Huestegge, Grainger, and Radach (2003) note that this is not the case for Glenmore (Reilly & Radach, 2003; 2006) as its letter and word module is an implementation of the multiple read-out model (Grainger & Jacobs, 1996) of isolated word recognition, and a similar approach was used by Kliegl and colleagues when designing SWIFT (Engbert et al., 2002; 2005; Richter et al., 2006). However, as Reichle et al. (2003) point out, simply inserting a well-specified word recognition model into a model of text reading is unlikely to provide a perfect solution, although there is evidence that slot-based coding can be rejected in both cases. Instead, as Radach and Kennedy (2004) suggest, the way forward might be for convergence of the results from both fields, provided that there is a theoretical analysis of the application of any findings to both other tasks and normal reading situations.

Chapter 3
The Orthographic Flanking Letters Lexical Decision Task
Introduction

Aims of the chapter

The literature presented so far has outlined the evidence for the processing of more than just the word being fixated during text reading, and ended by arguing the case for combining the traditions of isolated word recognition and eye movement control during reading which have so far remained separate. One way to approach the synthesis of findings from studies of isolated words and studies of text reading is to design a paradigm that combines aspects of both. This chapter presents the findings from a task which was designed to accomplish just this and also provides a simulation of text-level parafoveal-on-foveal effects with a single word.

The Flanking Letters Lexical Decision task

The Flanking Letters Lexical Decision task (FLLD) was devised to investigate how much the presence of parafoveal information affects isolated word processing by presenting a word for lexical decision flanked on either side by bigrams of letters (Dare & Shillcock, 2005). Figure 9 depicts the generic version of the paradigm, with whichever flanking letters are of interest presented around the central word. This combines a standard isolated word processing task with some of the direct letter context present around words in text.

xx word xx

FIG. 9: The generic Flanking Letters Lexical Decision task

The flanking bigrams act as primes for the central word, and this is a form of priming that can be thought of as spatial priming as the prime letters are presented simultaneously with the target response word. This is in contrast to the usual temporal priming, when the prime is presented prior to presentation of the target word. Temporal priming has previously been used by researchers to investigate visual, orthographic and lexical effects using isolated words. Parafoveal preview benefit was first discovered when Rayner et al. (1978) flashed preview words in the parafovea prior to presentation of a target word at that location. This task was an analogue of the investigation of parafoveal pre-processing during text reading using the boundary paradigm (e.g., Rayner, 1975). The finding that a parafoveal word can be processed prior to fixation is uncontroversial, and more recent research has instead focused on the possibility of simultaneous processing of parafoveal and foveal words (e.g., Kennedy, 1998). Spatial priming provides an analogue of parafoveal-on-foveal effects with isolated words, as the flanking bigrams are co-presented alongside the target word, and it is the impact of these flanking bigrams on processing of the central word that is of interest. In other words, temporal parafoveal priming assesses how much information is integrated across a saccade, whereas spatial parafoveal priming assesses how much information is integrated within a fixation.

This experiment will employ a simple version of the FLLD task, assessing the level of orthographic priming of the central word obtained when the flanking letters are derived from those in the central string compared to when the letters are unrelated (see Figure 10).

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wo word rd

le word sh
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FIG. 10: Related and unrelated flanking letters surrounding the target word in the Orthographic Flanking Letters Lexical Decision task

There are two major existing sources of evidence suggesting that orthographic priming effects are likely to occur. The first of these is the masked orthographic priming literature and the second is the parafoveal preview benefit literature mentioned above.

The evidence for orthographic priming

The first source of evidence for orthographic priming comes from straightforward foveal priming in which a prime is presented in foveal vision prior to presentation of a target word in the same position, typically with an intervening mask of unrelated letters such as x's. This technique was initially used by Forster and Davis (1984) who found that repetition of the target word speeded lexical decision compared to an unrelated prime. This priming stems, at least in part, from orthographic relatedness between the prime and target rather than lexical relatedness; this has been proved many times since then with the use of orthographically similar non-lexical stimuli which also provide priming compared to unrelated primes (*arple* primes *apple* whereas *table* does not; e.g., Peressotti & Grainger, 1999). Conversely, the prime and target do not have to be visually identical for orthographic priming to occur, as shown by the use of different cases for the prime and target (*LATE* acts as a prime for *late*; e.g., Evett & Humphreys, 1981). The extent to which a prime can differ from a target word and still provide orthographic priming has become an important topic of debate, as it informs the choice between slot-based and non slot-based forms of input coding to models of word recognition. The evidence for transposed-letters and relative-position priming effects (e.g., Andrews, 1996; Humphreys et al., 1990) provides support for models that do not rely on conjunctive coding of a letter's identity only within its position in a word (Davis & Bowers, 2006; Gómez et al., submitted; Grainger et al., 2006; Shillcock et al., 2000; Whitney, 2001).

The second and related source of evidence for orthographic priming effects can be seen in the work on parafoveal preview benefit (e.g., Rayner et al., 1978). Many studies have investigated which sources of information can be exploited in parafoveal pre-processing, and the conclusion is that while semantic similarities between the parafoveal prime and target word have no effect on target processing, orthographic overlap primes the target word (e.g., Balota & Rayner, 1983; Kwantes & Mewhort, 2002; Rayner, McConkie, & Zola, 1980a; Rayner & Morris, 1992). However, most of the work in this area has been carried out using word naming as the dependent variable, although experiments involving eye-tracking during reading have yielded similar results (Rayner, 1998).

Two additional studies have employed paradigms which have more in common with the current work than the studies discussed above. Pernet, Uusvuori, and Salmelin (2007) briefly presented primes in parafoveal vision prior to the target word for lexical decision, but they presented the target word at the initial fixation point, i.e., there was no saccade required (note that they mistakenly define this as parafoveal-on-foveal priming, whereas in the psycholinguistic literature the term parafoveal-on-foveal refers to the simultaneous presentation of parafoveal and foveal stimuli). They found the standard effect of decreased lexical decision times when parafoveal primes were repetitions of the foveal word compared to strings of consonants. While this paradigm is more similar to the current work than the parafoveal preview benefit paradigm as it does not involve a saccade, it is less useful than either as it does not simulate either parafoveal preview or parafoveal-on-foveal effects during reading. The FLLD task is instead a direct analogue of potential parafoveal-on-foveal priming.

Finally, Eriksen and Eriksen (1974) carried out a letter-based version of the FLLD task involving a decision as to which letter set (defined by a right or left lever-press response) a central letter belonged; the letters *H* and *K* formed one set and *S* and *C* formed the other. This central letter was flanked by distracter letters from the same or opposite letter set (compatible or incompatible respectively). As expected, incompatible flanking letters impaired processing of the central letter, and the authors concluded that the flanking letters were being processed simultaneously with the target letter to the point of response activation. Interestingly, Eriksen and Schultz (1979) compared the reaction times when the flanking letters were from the same response set (*H* flanked by *K*) and when they were identical to the central letter (*H* flanked by *H*), and found that responses were significantly faster when the flanking letters were identical even though both types of flanking letters belonged to the same lever-press response set. In other words, the response to the central letter was determined by the orthographic similarity of the flanking letters and not just the conditioned response set. They described a continuous flow model of visual processing in which some elements of an array are processed in parallel.

Use of the lexical decision task

The use of the lexical decision task to measure word recognition is uncontroversial and well-documented. Hundreds of experiments have used this paradigm when investigating lexical access and it is considered the 'gold standard' in word recognition, along with word naming (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004). Neither lexical decision nor word naming is a 'pure' measure of word recognition or a perfect analogue for silent reading as both require task-dependent additional processes of a word-nonword choice and an overt response of oral word production respectively. However, two reasons why lexical decision was preferred over naming are detailed below, and the conclusion is that the speech production element of naming renders it difficult to control.

The major concern with the naming task is that it requires irrelevant speech programming, which has both theoretical and practical ramifications. Results obtained using naming are not necessarily due to lexical access alone, but could be due to the act of articulation itself. Control words must be carefully chosen to be of similar syllabic complexity to target words, as the more complex an articulation, the longer its initiation (Sternberg, Monsell, Knoll, & Wright, 1978). A practical concern is the use of recording, as the end of the latency period is taken as being the recorded onset of the word. The words used must have a clear onset, or they will not trigger the voice key, and controls must be matched for consonant onset time. Words such as *sure* are not a good choice practically as stimuli, even if they are ideal theoretically, as the [ʃ] sound does not cause enough vibrations to register as the start of the word. Comparisons across tasks exemplify these problems. For example, Juhasz et al. (2003) found similar effects of the frequency of the ending lexeme of compound words in lexical decision, naming and silent reading, while effects of the frequency of the word-onset lexeme were only clear-cut in the naming task which can be attributed to the serial nature of articulation emphasising word-onset lexeme processing. Balota and Chumbley (1985) found that even after a delay of 1,400 msecs there was a frequency effect for word naming, highlighting the effect of the irrelevant speech programming. A final point concerns the fact that low-frequency irregular words are named more slowly than low-frequency regular words (the regularity effect). Coltheart and Rastle (1994) found that this effect interacts with the position of the irregular component of the word, with irregular word onsets (*chef* vs. *chief*) slowing naming speed more than irregular word endings (*swap* vs. *snap*). Those carrying out naming tasks therefore have the additional burden of controlling for the serial position of any irregular spelling.

Although there are problems with the lexical decision task that reduce its utility in some situations, these do not apply to the orthographic FLLD task. One criticism is that it is more sensitive to lexical frequency effects than naming or reading (Balota & Chumbley, 1984; Schilling et al., 1998). This arises from its dependence on visual familiarity as lexical decision requires discrimination of words from non-words based on visual information, thus highlighting the similarity between low-frequency words and non-words and slowing responses to low-frequency words. However, this emphasis on visual processing makes it an ideal task for assessing the impact of parafoveal visual information in the orthographic FLLD paradigm. The orthographic priming in the FLLD paradigm also answers the criticism that the lexical decision task is disproportionately affected by semantic and syntactic contextual influences (Balota & Chumbley, 1984; Seidenberg, Waters, Sanders, & Langer, 1984). Additionally, the majority of work assessing parafoveal preview benefit for isolated words was carried out using naming as the dependent variable (Rayner, 1998).

The current experiment

The design of this experiment will follow that of Dare and Shillcock (2005) who first introduced this paradigm. There are three conditions in this experiment: Adjacent bigrams, Reversed bigrams and Unrelated bigrams. The first two conditions contain bigrams whose letters are the same as those in the central letter string, and the Unrelated condition acts as a control. Figure 11 presents the three experimental conditions.

`ro rock ck` *(Adjacent)*

`ck rock ro` *(Reversed)*

`le rock sh` *(Unrelated)*

FIG. 11: The three flanking letters conditions in the current version of the Orthographic Flanking Letters Lexical Decision task

Predictions

The Adjacent and Reversed conditions allow for investigation of the effects of letter order versus letter identity in orthographic priming, as if correct letter order and identity are both vital for orthographic priming (as predicted by word recognition models whose input depends on slot-based coding such as the IAM; McClelland & Rumelhart, 1981) then the Adjacent bigrams should provide more priming. However, if letter identity is more important than letter order (as predicted by word recognition models such as SERIOL; Whitney, 2001) then the Adjacent and Reversed bigrams should provide similar levels of priming. Based on the orthographic priming literature outlined above, the clear prediction for the Unrelated condition is that it will provide no facilitation compared to the two related bigrams conditions. These predictions will be tested by comparing both lexical decision times and response accuracy across the three conditions: reduced lexical decision times and increased accuracy scores indicate priming.

Direct support for these predictions comes from the findings of Dare and Shillcock (2005) who showed that lexical decision response times were approximately 25 milliseconds slower in the Unrelated condition than in the Adjacent or Reversed conditions, but that the Adjacent and Reversed conditions did not differ from each other. Following on from their work we will also compare the response times and accuracy scores to low and high frequency words, with the prediction that high frequency words will elicit faster and more accurate responses than low frequency words. Fixation lines will be presented above and below the centre of the target word prior to the experimental presentation to ensure fixations fall on the target word, and not on the bigram primes. However, on this point the current work will deviate from that of Dare and Shillcock (2005) by introducing limited exposure duration for the presentation. In the FLLD task used by Dare and Shillcock (2005) the stimulus remained on-screen for the duration of the lexical decision, and as typical responses were in the order of 700 milliseconds there was ample time for execution of an eye movement to the flanking bigrams themselves. Grainger, O'Regan, Jacobs, and Segui (1992) point out that if information is presented for less than 170 msecs it can be assumed that any processing was of information obtained during the first fixation only. We therefore decided to present the target word and accompanying bigrams for only 150 msecs. The predictions for the results of this experiment are unchanged following this amendment, as Grainger et al. (1992) found very similar orthographic neighbourhood effects in a lexical decision task carried out first with an unlimited viewing time and then with the stimuli presented for 160 msecs.

Method

Participants

36 students at the University of Edinburgh participated in the experiment in return for payment of £2.50. There were 15 males and 21 females, ranging in age from 17 to 32 years (mean age = 21 years, *SD* = 3 years). All participants were native English speakers with normal or corrected-to-normal vision. 28 participants were right eye dominant, and eight were left eye dominant, tested by asking participants which eye they would use to look through a keyhole or down a tube. None had any language disability. Participants' handedness was also recorded in order to allow a direct comparison with the work by Dare and Shillcock (2005) who had recorded handedness to ensure that only right-handed participants were included; this was to avoid any effects of heterogeneity of language lateralisation. The Edinburgh Handedness Inventory (EHI; Oldfield, 1971) was used to formally assess handedness. It is a 10-item test concerning the hand used to carry out a range of everyday tasks. Its scores range from 10 (most right-handed) to -10 (most left-handed), with 0 indicating ambidextrousness. All of the participants both self-reported as right-handed and were rated as right-handed on the EHI with a mean score of 6 and a range of 2-10.

Materials

Every stimulus presentation had the same format, of a central four-letter string flanked on either side by a bigram. 144 words and non-words were used, making a total of 288 experimental stimuli. The words were taken from the MRC psycholinguistic database (Coltheart, 1981). All word types were included, but no proper names or taboo words were used. In order to investigate the possibility that word frequency would interact with the flanking bigram condition, half of the words chosen were those considered to be of high frequency (frequency > 200, mean = 877), and half were those considered to be of low frequency (frequency = 1; Kucera & Francis, 1967). Both the low and high frequency lists contained nouns, verbs, adjectives and participles, but the high frequency list contained words from more varied parts of speech, such as adverbs (*away*), prepositions (*from*), auxiliaries (*have*) and pronouns (*them*; see Appendix 1 for full word list). The 144 non-words used were taken from the ARC database (Rastle, Harrington, & Coltheart, 2002). They contained only orthographically legal bigrams but not those that formed stand-alone words (see Appendix 1 for non-word list).

In the Adjacent and Reversed conditions, the flanking bigrams used were the first and last bigrams of the central string. In the Unrelated condition, bigrams were created by splitting unused four-letter non-words into halves and presenting one on either side of the central string. For example, in the Adjacent or Reversed conditions, when the central string was *wife* then the bigrams were *wi* and *fe*; in the Unrelated condition the bigrams were *mu* and *rp* from the non-word *murp* that was not used as a central string. Only orthographically legal bigrams were used, but no stand-alone two-letter words were used in any condition so that there would be a maximum of only one lexical entry in any given stimulus presentation. Therefore, the bigrams *am*, *an*, *as*, *at*, *be*, *by*, *do*, *he*, *if*, *in*, *is*, *it*, *me*, *my*, *no*, *of*, *on*, *or*, *so*, *to*, *up*, *us*, and *we* were excluded, as were any words or non-words whose first and last bigrams were one of these bigrams.

All of the stimuli were presented in bold lowercase 14-point Courier New (a monotype font) and preceded by a pair of fixation lines above and below the centre of the target letter string. An example of the presentation for each condition is below.

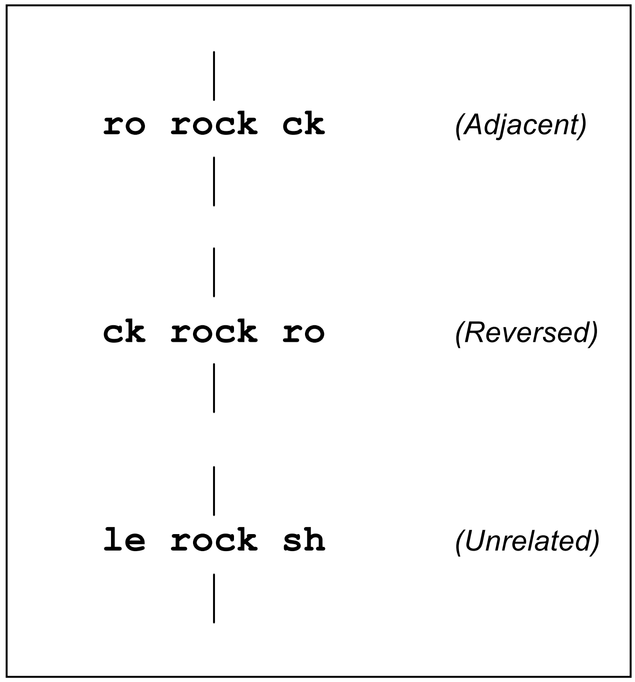

FIG. 12: The three flanking letters conditions in the Orthographic Flanking Letters Lexical Decision task

Design

A 3x2 within-subjects design was used, with bigram order as one variable with three levels (Adjacent, Reversed and Unrelated) and lexical frequency as the other variable with two levels (high and low). Each participant could only see each string once in the experiment, in the Adjacent, Reversed or Unrelated condition. Therefore, three versions of the experiment were created, with 12 participants for each version. The 144 words and non-words were divided equally into three groups of 48 words and non-words. Each word group was assigned to one experimental condition in each version, using a counterbalanced Latin Square design. Each of the three groups had equal numbers of low and high frequency words. Other than this frequency constraint, the words and non-words were divided randomly.

In order to avoid any practice or fatigue effects, the stimuli were presented in two halves, with 24 words and non-words in each experimental condition in each half using a Latin Square design. The halves were also identical in terms of number of high and low frequency strings, so each half represented the entire experiment, but with half of the stimuli.

A final consideration was the method by which participants indicated their word/non-word decision using different buttons on a button box. As we were concerned with avoiding handedness or hemispheric effects, and there is exclusive contralateral control of the hands by the brain, different responses were not indicated by different hands. Instead, in order to engage both hemispheres on every trial, participants used both hands to indicate each decision, with the different responses indicated by the different fingers used (following Mohr, Pulvermüller, & Zaidel, 1994). Therefore, two further versions of the experiment were created, with either the index fingers or the middle fingers indicating a word, again using a Latin Square design. Twelve versions of the experiment were therefore required.

Procedure

Participants were first asked to complete the EHI, including a question about their eye dominance (i.e., the eye they would use to look down a telescope or microscope). Their non-dominant eye was covered with an eye-patch so that participants could not look at the screen using both eyes, as Heller and Radach (1999) and more recently Liversedge, White, Findlay, and Rayner (2006) reported a disparity in fixation between the eyes of more than 1 letter during normal word reading. To ensure fixation and therefore foveation of the central string, participants were only able to see the screen with their dominant eye.

They were informed that the experiment was about recognising words, and were given both verbal and written instructions about their task. These included details of the fixation lines, flanking bigrams, and response method. They were also asked to respond as quickly and accurately as possible. 12 practice strings (four of each of the experimental conditions) were presented before the experimental stimuli, and the results from the first two strings of each half of the experiment were discarded (they were foils, and identical in every version).

Each trial began with a 1000 msecs presentation of two vertical fixation lines above and below the centre of the screen (following Brysbaert, 1994). This was replaced by the central string, laid out such that the centre of the string, between letters two and three, was at the fixation point. The flanking bigrams were on either side of the central string, at a distance of one space. In order to ensure that no eye-movements were made during presentation of the stimuli, the targets remained on the screen for only 150 msecs (following the assumption of Grainger et al. (1992) that for a stimulus presented for less than 170 msecs the only processing that will occur is of information obtained during the initial fixation). The lexical decision was indicated by the participants pressing the appropriately labelled buttons on a button box with either the index or the middle fingers of both hands. The response was followed by a blank screen that lasted for 1000 msecs. There was a break half way through the experiment.

The procedure was implemented using the experimental presentation software E-Prime (version 1.1) on a Pentium IV PC. After completing the experiment, participants were asked about their experience, and none had identified the motivation for the experiment. They were then given debriefing information. The entire session lasted about 20 minutes.

Data selection

Reaction times more than 2.5 standard deviations away from the grand mean were considered to be outliers and removed. They were replaced by the mean of the participant or item in that condition for the purposes of assessing reaction times, but for accuracy counts they were simply discarded.

The reaction time data to incorrect responses and non-word responses were discarded as they were of no experimental interest. Although both hands were used to indicate each response, the faster response of the two was considered to be the reaction time. Mean reaction times for each level of the bigram order and frequency variables were calculated for each participant and item.

Accuracy scores were defined as the number of correct responses made after removal of outliers; these were out of 24 per condition for participants and out of 12 per condition for items.

Data of this kind are typically analysed using a combination of F1 and F2 ANOVA analyses, with the F1 analysis assessing the mean behavioural scores for each subject and the F2 analysis assessing the mean behavioural scores for each item. These allow the researcher to claim that their findings are generalisable across subjects and items respectively. However, there are several problems with these analyses. For example, ‘rogue’ behaviour by one subject or item can lead to or mask significant effects, as the F1 analysis assumes that there is no meaningful variance attributable to the items sample and the F2 analysis assumes this to be the case for the subjects sample. Additionally, if one test is significant but the other is not then it is difficult to draw conclusions about the experiment.

Recently, there has been a call for an analysis method capable of dealing with variance in both the subjects and items samples simultaneously; in particular, Brysbaert (2007) and Baayen, Davidson, and Bates (2008) have argued convincingly for the use of linear mixed-effects (LME) modelling as this allows the researcher to disregard both which participant was being tested and which item they were responding to when calculating the effect of one or more IV’s on behaviour. Simply put, the response of a subject reacting to an item manipulated in a designated manner is due to the nature of three things: the subject, the item and the manipulation (plus some error). The experimenter is solely interested in the effect of the manipulation (a fixed effect) and not the effect of the identity of the subject or item (random effects). In the analysis the experimenter indicates that the random variables have different intercept values; in other words, subject 1 might have a different baseline response time than subject 2, as they have been randomly drawn from the population, but it is the impact of the fixed effect(s) on those baselines that is of interest. A more conservative alternative is to indicate that both the intercept and slope of the random variables have different values, but the default option of random intercepts only will be used.

LME analysis assesses the significance of a model that predicts variance only over and above that predicted by the identity of the subject and item. Thus, the need for separate subject and item analyses is removed, and an F-value is obtained which holds for both. Therefore, LME analyses complementary to the traditional ANOVA will also be reported for all experiments. However, non-numeric variables, such as accuracy which has a binary outcome, require a logistic LME analysis which, although more appropriate than ANOVA, is difficult to carry out using the standard analysis tool SPSS. This consideration, combined with the fact that the variables of most interest are numeric, means that only the more straightforward non-logistic LME analysis will be carried out.

Results

Reaction times

As Table 1 and Figure 13 show, reaction times to high frequency words were approximately 90 msecs faster than reaction times to low frequency words, and reaction times in the Unrelated condition were about 20 msecs slower than those in the two related bigrams conditions.

A two-way repeated-measures ANOVA found that there was a main effect of bigram condition [$F_1(2,70) = 9.24$, $p < 0.001$; $F_2(2,284) = 8.65$, $p < 0.001$]. Post-hoc t-tests with a Bonferroni correction showed the Unrelated condition was significantly slower than the Reversed condition [$t_1(35) = 3.66$, $p < 0.01$; $t_2(143) = 3.62$, $p < 0.001$] and the Adjacent condition [$t_1(35) = 3.32$, $p < 0.01$; $t_2(143) = 3.80$, $p < 0.001$], but that there was no significant difference between the Reversed and Adjacent conditions [$t_1(35) = 0.00$, *ns*; $t_2(143) = 0.10$, *ns*]. Similar results were obtained with an LME analysis [$F(2,4456.67) = 10.53$, $p < 0.001$; Unrelated-Reversed $t(4457.35) = 3.82$, $p < 0.01$; Unrelated-Adjacent $t(4457.15) = 4.12$, $p < 0.01$; Reversed-Adjacent $t(4455.50) = 0.29$, *ns*].

There was a significant main effect of word frequency [$F_1(1,35) = 148.69$, $p < 0.001$]; for the items analysis this was a between-items analysis [$F_2(1,142) = 190.10$, $p < 0.001$], with inspection of the means indicating that the reaction times to the high frequency words were faster than those to the low frequency words. This was confirmed with an LME analysis [$F(1,123.89) = 205.04$, $p < 0.001$].

There was no significant interaction between bigram order and frequency [$F_1(2,70) = 0.078$, *ns*; $F_2(2,284) = 0.11$, *ns*; LME $F(2,4456.66) = 0.26$, *ns*].

TABLE 1

Mean reaction times (and standard deviations) as a function of word frequency and bigram order.

	Bigram order		
	Reversed	Adjacent	Unrelated
Reaction time (milliseconds)			
High frequency words	654.7 (107.7)	655.0 (124.5)	677.1 (117.0)
Low frequency words	765.0 (109.4)	764.8 (123.3)	791.8 (111.5)

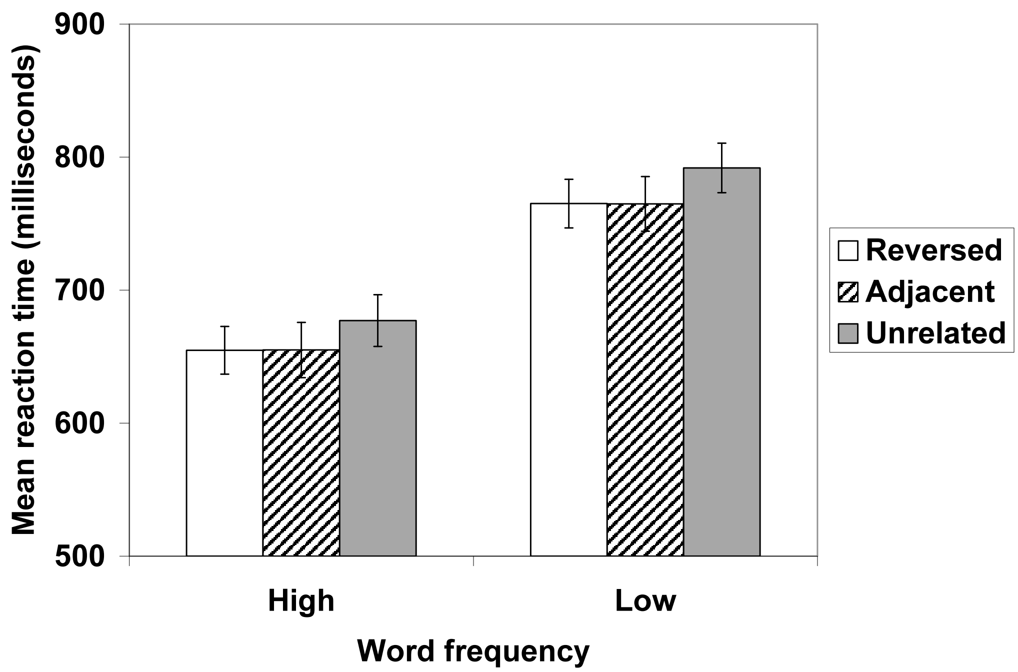

FIG. 13. The effect of frequency and bigram condition on lexical decision reaction times; error bars indicate standard error of the mean.

These results support the prediction that related flanking letters decrease response times, but no difference was found between the related letters conditions. They also support the prediction that high frequency words elicit faster response times than low frequency words.

Accuracy scores

As Table 2 and Figure 14 show, the accuracy of lexical decisions appears to be lower for the low frequency words than for the high frequency words, but bigram condition appears to make little difference.

A two-way repeated-measures ANOVA showed that there was no main effect of bigram order on the accuracy of decisions [$F_1(2,70) = 1.53$, *ns*; $F_2(2,284) = 1.79$, *ns*]. As indicated by the means there was a main effect of word frequency [$F_1(1,35) = 72.99$, $p < 0.001$]; for the items analysis this was a between-items analysis [$F_2(1,142) = 49.85$, $p < 0.001$].

There was no interaction between bigram condition and word frequency [$F_1(2,70) = 0.28$, *ns*; $F_2(2,284) = 0.33$, *ns*].

TABLE 2

Mean accuracy scores (and standard deviations) as a function of word frequency and bigram order.

	Bigram order		
	Reversed	Adjacent	Unrelated
Accuracy scores (out of 24)			
High frequency words	23.1 (1.2)	23.2 (1.3)	22.9 (1.6)
Low frequency words	19.8 (3.0)	20.3 (2.7)	19.8 (3.2)

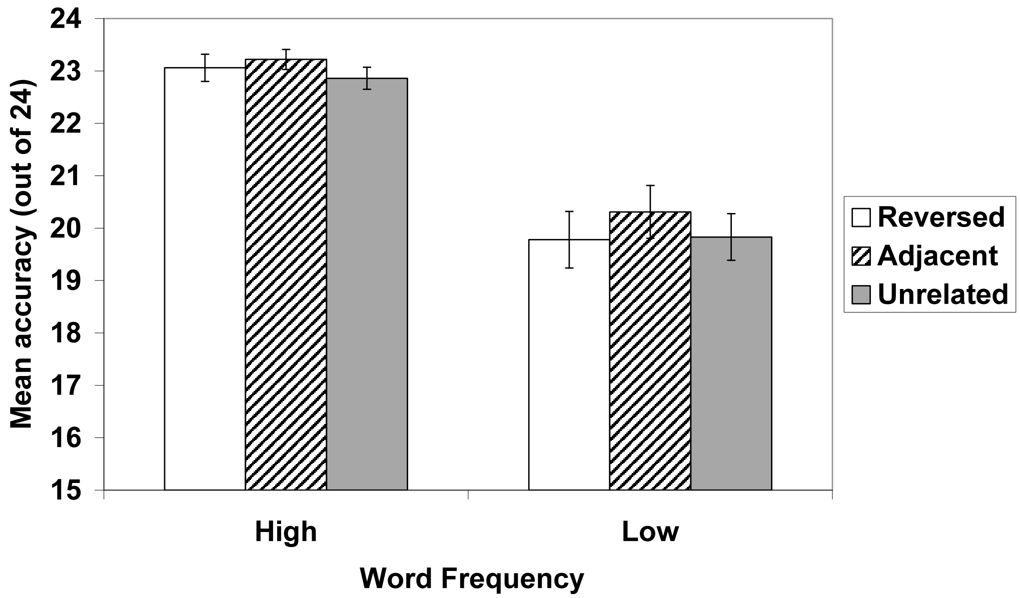

FIG. 14. The effect of frequency and bigram condition on lexical decision accuracy scores; error bars indicate standard error of the mean.

The accuracy scores again support the prediction that responses to high frequency words are more accurate, but accuracy scores did not reflect any priming in the two related bigrams conditions.

Discussion

Flanking letters predictions

This experiment was designed to extend the work of Dare and Shillcock (2005) by comparing reaction times and accuracy following lexical decision to a four-letter word flanked by orthographically related or unrelated bigrams, a paradigm known as the Flanking Letters Lexical Decision task. The FLLD task provides both the advantages of a tightly controlled isolated word paradigm and the opportunity to assess the effects of the immediate letter context present in text. It also acts as an isolated word analogy for the parafoveal-on-foveal effects observed during reading. The key difference in this experiment was the use of briefly presented stimuli to ensure that the flanking bigrams could not undergo direct inspection. Thirty-six participants responded to both high and low frequency words in three flanking bigrams conditions: Adjacent, Reversed and Unrelated. Following Dare and Shillcock (2005), the predictions were that lexical decision times would be reduced in both the Adjacent and Reversed conditions compared to the Unrelated condition, and for the high frequency words compared to the low frequency words. It was expected that accuracy scores would show the converse of the response durations. The two related bigrams conditions allowed for comparison of the importance of letter identity and position.

In general, the lexical decision duration results followed those of Dare and Shillcock (2005). Firstly, responses to the high frequency words were significantly faster than those to the low frequency words. This robust lexical frequency effect has been repeated many times throughout the word recognition literature (e.g., Forster & Chambers, 1973), and indicates that despite the bigram manipulation processing of the central word demonstrates this robust linguistic effect. Secondly, response durations were reduced when the flanking bigrams were orthographically related to the central word. This finding is in line with multiple word naming experiments demonstrating orthographic priming effects from primes presented at both foveal and parafoveal positions, although the simultaneous presentation of primes and lexical stimuli is novel. This spatial orthographic priming implies that we are taking in information from around the word of interest during its processing and that there is parallel orthographic processing across the visual field within the duration of one fixation.

Thirdly, there was no significant difference between the response times to the Adjacent and Reversed conditions, both of which were orthographically related to the central word. The crucial difference between these conditions was that the flanking bigrams in the Adjacent condition retained the same letter order as the target word while the bigrams in the Reversed condition did not. Models of word recognition reliant upon strict slot-based coding of letters would probably predict that the Adjacent condition provides more priming i.e., faster lexical decision times than the Reversed condition. That the priming levels were identical exemplifies the accumulating body of evidence in favour of alternative input styles such as open bigrams (Overlap Open-Bigram model, Grainger et al., 2006; SERIOL, Whitney, 2001) or spatial coding (Davis & Bowers, 2006). The current experiment cannot distinguish between these models, although it is perhaps suggestive that no response advantage was found in the Adjacent condition compared with the Reversed condition even though in the former the order of the exterior letters was maintained. The SERIOL model (Whitney, 2001) places more emphasis on exterior letters than interior letters and predicts that there should be more priming from an orthographically related stimulus whose exterior letters are in their correct positions; this was not the case in this experiment.

As is typically found, the accuracy scores did not match the predictions as clearly as the lexical decision times did. Although accuracy of response was significantly greater for the high frequency words, bigram condition had no impact. Given the clear priming from related bigrams shown in the response times, it seems more likely that accuracy is simply not significantly affected by the bigram condition rather than that orthographic priming does not occur. Accuracy levels have no obvious analogue in text reading in which nonwords are extremely uncommon, and so they were of secondary interest to the response time data which parallel fixation durations during reading.

Future work

The orthographic FLLD task can easily be extended in much the same way that foveal masked priming experiments have been to test a variety of more subtle effects predicted by the various word recognition models. Figure 15 illustrates some of these possible extensions. Extension 1 is a reversed-letters prime (which violates relative letter order) and 2 is a substituted-letters prime (which violates letter identity); thus all of the non slot-based coding models would predict less priming from these conditions than either the Adjacent or Reversed conditions. SERIOL (Whitney, 2001) would predict more priming from extension 2 than extension 3 as extension 3 removes exterior letter information. It would also predict more priming from extension 4 than extension 5 as it gives increased weighting to initial than final bigrams.

ow word dr	*(1)*
w# word #d	*(2)*
#o word r#	*(3)*
wo word ##	*(4)*
## word rd	*(5)*

FIG. 15: Possible extensions of the Orthographic Flanking Letters Lexical Decision task

However, although this experiment fulfils its remit as an analogue of parafoveal-on-foveal processing effects in text by providing evidence for parafoveal orthographic processing during lexical access a clearer test would, of course, come from a demonstration of orthographic priming in a text reading task, and it is to eye-tracking during sentence reading that this thesis now turns.

Chapter 4
The Repeated Word n+1 Parafoveal-on-Foveal Task
Introduction

Aims of the chapter

The previous experiment clearly demonstrated that the presence of orthographically related flanking letters presented simultaneously with a target word reduces lexical decision durations to that word. This finding suggests that orthographic information from an isolated word and its surroundings is being processed in parallel, but is this also the case during reading? The isolated word result could be due to the simplicity of the task employed and the conscious awareness of the related parafoveal letters. It is also not possible to determine whether the orthographic priming comes from facilitation (due to twice the orthographic information) or reduced inhibition compared to the Unrelated letters condition (as the unrelated letters acted as distractors; see Eriksen & Eriksen, 1974). In a similar manner, Rayner, White, et al. (2003) criticised the early parafoveal-on-foveal work (e.g., Kennedy, 1998) for its lack of ecological validity. In order to investigate potential orthographic parafoveal-on-foveal effects during reading, this experiment will instead present sentences containing a boundary change to mask the presence of a repetition of the target word at the word n+1 location.

Previous orthographic parafoveal-on-foveal studies

As discussed extensively in Chapter 2, the importance of parafoveal-on-foveal effects lies in their potential as evidence for parallel processing of text. If the properties of a peripheral word can affect the processing of a fixated word this strongly implies that they are being processing simultaneously, at least to an extent. The issue of serial versus parallel processing is particularly vexed due to two influential models of eye movement control relying on one or other mode of processing: E-Z Reader (Reichle et al., 1998) is predicated upon serial shifts of attention between words while SWIFT (Engbert et al., 2002) advances the theory of parallel attention spread across multiple words. At present the evidence for parafoveal-on-foveal effects is mixed, so a clear demonstration of their presence or absence is an interesting and important finding.

Several studies have focused on orthographic-level parafoveal-on-foveal effects with predominantly positive results. The most common investigation has been of the effect of presenting an orthographically illegal non-word (such as *bvlkn*) at the post-boundary position in an eye-movement contingent display change paradigm. Inhoff, Starr, et al. (2000) and Starr and Inhoff (2004) both showed that illegal parafoveal orthography serves to increase pre-boundary target viewing durations. Corresponding work by Pynte et al. (2004) presented an initial-letter "typo" at the post-boundary position. When the typo rendered the word orthographically illegal the preceding article word was less likely to be skipped, and when the typo did not affect orthographic legality first fixation and gaze durations on word n-2, always a longer content word, were reduced. However, White and Liversedge (2004) failed to replicate these results of parafoveal misspellings.

Two studies of more direct relevance to the current work on orthographic priming were conducted by Vitu et al. (2004) and Inhoff, Radach, et al. (2000). Vitu et al. carried out eye-tracking of pairs of words that were either orthographic neighbours (such as *pour* and *four*) or unrelated orthographically (such as *pour* and *clan*) during participants' inspection of these word pairs for animal names. Orthographic priming was in this case indicated by reduced single fixation and gaze durations on the first word when the pairs were related. A more naturalistic reading task was employed by Inhoff, Radach, et al. who assessed eye-movement responses to a target word followed by a post-target word that was a repetition of the target word. This task included sentences such as *Did you see the picture of her mother's mother at the meeting?*. First fixation and gaze durations on the target word (in this case *mother's*) were reduced when the post-target word was a repetition, compared with the control condition of an unassociated post-target word. This is further evidence for parafoveal-on-foveal orthographic priming effects, and Inhoff, Radach, et al. concluded that more than one word can be processed during a fixation such that the properties of a parafoveal word can influence processing of the fixated word. However, this word repetition led to unnatural sounding sentences, and it is possible that participants became aware that the repetitions were an important part of the experiment. Additionally, although the authors stated that participants were encouraged to read for meaning their understanding was assessed infrequently. What is instead required is a paradigm that incorporates naturalistic reading of fluent sentences with an element of parafoveal orthographic priming, and the boundary paradigm (Rayner, 1975) provides just that.

The boundary paradigm

The boundary paradigm (Rayner, 1975) was briefly introduced in the course of Chapter 2 (see Figure 5), but its widespread use in both the literature and in this thesis warrants a closer inspection of this task. It involves the use of a pre-programmed boundary set up at the desired location on a display screen that allows the experimenter to control the presentation of material dependent on the fixation position of the viewer. In a typical reading experiment involving the boundary paradigm (e.g., Balota et al., 1985) the boundary is positioned between two words, with some property of the post-boundary word altering once the eye crosses the boundary. This boundary is invisible to the viewer and is located in a position that is unlikely to undergo direct inspection (hence, in the space between two words). This results in the boundary change occurring during a saccade when visual suppression acts to mask any visual changes (see Wurtz, 2008), rather than during a fixation.

This paradigm was explicitly developed to allow experimental manipulation of peripheral processing while providing the viewer with the conscious sensation of normal reading. Many different experimentally motivated changes can be made to the post-boundary text, but as this amended text is replaced with appropriate text once the boundary has been crossed, meaningful reading can continue. However, any changes tend to be small-scale in the sense that they do not disrupt the overall presentation of the text; in other words, changes tend to be localised within words and the post-boundary text follows the same pattern of characters and spaces as it did during the pre-boundary phase. This reduces the possibility that the viewer will notice the presence of the boundary, a desirable situation for a paradigm designed to minimise disruption of normal reading patterns. If participants routinely spotted that changes to the text were happening while they were reading it could affect their eye movement pattern, although it has been experimentally determined that screen flicker and phosphor persistence created by the boundary change have no impact on this pattern (Inhoff, Starr, Liu, & Wang, 1998).

This paradigm has most frequently been employed in the area for which it was designed, the investigation of the parafoveal preview of text prior to its fixation and direct inspection (see Rayner, 1998, for a review). The type of information available for preview is determined by the post-boundary viewing durations as a function of the post-boundary stimulus type presented. Its appeal for those wishing to study the potential parallel processing of text is clear, as in these cases it is the pre-boundary viewing durations as a function of post-boundary stimulus type that determine the existence of parafoveal-on-foveal effects. A major concern with the early work on parafoveal-on-foveal effects (e.g., Rayner, White, et al., 2003) was that it involved tasks other than reading of text (Kennedy, 1998; 2000; Murray, 1998; Murray & Rowan, 1998), but the use of the boundary paradigm in later work renders it immune to such criticism and provides consistent findings of parafoveal-on-foveal effects with ecological validity (e.g., Inhoff, Starr, et al., 2000; Underwood et al., 2000).

The current experiment

This experiment involved an extension of the work by Inhoff, Radach, et al. (2000) using the boundary paradigm (Rayner, 1975) to avoid overt repetition of the target word. To avoid confusion, in this experiment the word immediately to the left of the boundary was called the pre-boundary word, the word immediately to the right of the boundary that is presented prior to the boundary change was called the parafoveal word, and the semantically appropriate word immediately to the right of the boundary presented after the boundary change was called the post-boundary word. Parafoveal-on-foveal effects are therefore the influence of the properties of the parafoveal word on the processing of the pre-boundary (or target) word. Three parafoveal word conditions were compared: Repeated (parafoveal word is a repetition of the target word), Control (parafoveal word is orthographically unrelated to the target word) and Baseline (no boundary change). Figure 16 displays these three conditions prior to the boundary change.

The store had a *coat* | *coat* that week *(Repeated)*

The store had a *coat* | *milk* that week *(Control)*

The store had a *coat* | *sale* that week *(Baseline)*

FIG. 16: The Repeated, Control and Baseline conditions prior to the boundary change (target, parafoveal and post-boundary words in italics; the dashed line indicates the boundary position)

In order for normal reading to progress the Repeated and Control parafoveal words were replaced with the Baseline parafoveal word following the boundary change. This allows both covert orthographic priming and meaningful reading processes to occur. Participants' eye movements during reading of these sentences were recorded. In order to ensure meaningful reading, comprehension questions will frequently follow the sentences. An advantage of the use of a text reading paradigm is that it allows for clearer understanding of the mechanism by which any orthographic priming occurs. In text, words are surrounded by other words whose letter identity and order generally do not match those of the fixated word. This is similar to the Unrelated letters condition of the Orthographic FLLD task except that in text these unrelated letters are expected and do not distract from the fixated word; thus, any orthographic priming can be attributed to repeated letters facilitation rather than reduced unrelated letters inhibition.

Replication of the Orthographic FLLD results using eye-tracking

Is it likely that the parafoveal orthographic priming demonstrated by the orthographic FLLD results will be replicated in the eye movement patterns recorded during text reading? More specifically, does the finding of reduced lexical decision latencies to isolated words in the presence of related letters increase the likelihood for parafoveal-on-foveal effects from orthographic priming? The results of direct comparisons between isolated word and text reading paradigms outlined in the Literature Review suggest that this is likely as many of the same effects are found using both types of task. These include lexical frequency effects (Juhasz et al., 2003; Schilling et al., 1998), orthographic effects (Johnson et al., 2007; Perea & Pollatsek, 1998) and phonological effects (Folk & Morris, 1995; Pollatsek et al., 1992).

However, there are two comparisons whose negative findings suggest accommodative adjustments to the current experiment. The first is that of Briihl and Inhoff (1995) who found that parafoveal preview benefits were only seen for the initial but not the final letter of a parafoveal preview word despite the prominent role often assigned to both the exterior letters of isolated words. Inhoff et al. (2003) explain this discrepancy as being due to acuity limitations on the processing of the end letters of a parafoveal word, whereas Miellet, O'Donnell, and Sereno's (submitted) finding that magnification of parafoveal letters does not increase the amount of text undergoing processing led them to suggest an attention-based reduction of parafoveal processing. Whichever explanation is correct, in order to avoid null findings based on reduced parafoveal processing this experiment will not include very long target words which would cause the parafoveal word to fall too far into peripheral vision. The second finding is that although Schilling et al. (1998) found lexical frequency effects in naming, silent reading and lexical decision they were more pronounced in the lexical decision task. This is evident in the clear frequency effect demonstrated by the reaction time and response accuracy data of the Orthographic FLLD task. There will therefore be no partitioning by frequency in this experiment, but rather the target words will cover a large range of frequencies to ensure that any results apply to most normal reading situations.

Predictions

The main prediction for this experiment is that there will be reduced pre-boundary target viewing durations when the parafoveal word is a repetition of the pre-boundary word. That is, fixation durations on the pre-boundary word will be shorter in the Repeated condition than in the Control condition. This prediction follows from the demonstrations of parafoveal orthographic priming in isolated words (the Orthographic FLLD task), in text (Inhoff, Radach, et al., 2000; Vitu et al., 2004) and the accumulating evidence for orthographic parafoveal-on-foveal effects using the boundary technique (e.g., Starr & Inhoff, 2004). Any potential effects can only be assessed using first-pass measures such as first fixation duration, gaze duration and fixation probability, as once the eyes have moved to the right of the pre-boundary word the boundary change means that the post-boundary word is subsequently displayed. An even stronger prediction of parafoveal orthographic priming is that fixation durations on the pre-boundary word will be shorter in the Repeated condition than in the Baseline condition, even though the semantic plausibility of the parafoveal word in the Baseline condition should serve to reduce fixation durations on the pre-boundary word (see Murray, 1998, and Murray & Rowan, 1998, for details). This follows from the findings of Inhoff, Radach, et al. (2000) in which fixation durations on the target word were reduced when it was repeated compared to when a baseline sentence was presented. However, as discussed above, the overt repetition of the target word in this work could have exaggerated its effect, so this is a tentative prediction.

A standard parafoveal preview analysis will also be carried out to assess the impact of parafoveal pre-processing on post-boundary word responses. In line with the multitude of studies on this topic the prediction is that when the post-boundary word is always available for inspection, as in the Baseline condition, fixation durations on the post-boundary word will be reduced compared to when an unrelated word is presented prior to fixation, as in the Control and Repeated conditions (e.g., Balota et al., 1985; Inhoff & Tousman, 1990; Rayner, 1975). Fulfilment of this prediction of parafoveal preview benefit is a good indicator that the experiment paradigm conforms to previous work.

Method

Participants

30 University of Edinburgh students participated in this experiment. They were each paid £10 for their time. All of the participants were native speakers of English with no reading disabilities and normal or corrected-to-normal vision.

Design

There were three conditions in this experiment: Baseline (no boundary change), Control (unrelated word n+1) and Repeated (repeated word n+1). Each participant was presented with 69 experimental sentences, with 23 in each condition. The sentences were counterbalanced across the three conditions to make three versions of the experiment with 10 participants per version.

Materials

The stimulus materials used were sentences that fit onto a single line across the computer screen and ranged from 44 to 64 characters in length. There were 69 experimental sentences and 50 fillers, making a total of 119 sentences for participants to read. Each experimental sentence contained a target word either four or five letters long taken from the MRC psycholinguistic database (Coltheart, 1981); 39 four-letter and 30 five-letter words were used. To ensure that the identity of the target word remained unknown the word type of the target words included a mixture of nouns, verbs and adjectives. Following the finding that when foveal load is high there is no effect of parafoveal word informativeness (Kennedy et al., 2002) and that increased foveal load decreases parafoveal processing (Henderson & Ferreira, 1990) the frequency count of the target word was at least 40 counts per million but not greater than 399 counts per million (Kucera & Francis, 1967). This upper limit on frequency and the avoidance of function words also helped to reduce the probability of word skipping. To ensure a basic similarity between the experimental and filler sentences a four- or five-letter word with the same selection criteria as the target words was used in every filler sentence. 30 four-letter filler and 20 five-letter filler sentences were constructed. All sentences were presented in 19-point bold black text in the monotype font Courier on a white background.

This target word was followed by an invisible boundary located at the pixel immediately to the right of the target word. The experimental manipulation in this study was of the word presented to the right of this boundary until the point at which the eyes crossed the boundary (this will be referred to as the parafoveal word). After the boundary was crossed the parafoveal word was replaced with a word chosen to produce a meaningful sentence so that the viewer was unaware of the manipulation (this will be referred to as the post-boundary word). This post-boundary word was of the same length (either four or five letters) and similar frequency (maximum difference of 12 counts per million) as the target word. The target and post-boundary words never occupied the first or last positions in a sentence. Figure 17 illustrates the use of the invisible boundary paradigm and the three parafoveal word conditions.

The store had a *coat* *coat* that week (Repeated)
                *
The store had a *coat* *milk* that week (Control)
                *
The store had a *coat* *sale* that week (Baseline)
                *
The store had a *coat* *sale* that week (post-boundary)
                     *

FIG. 17: The three parafoveal word conditions and the boundary change (target, parafoveal and post-boundary words in italics; dotted lines indicate the boundary position; asterisks indicate fixation position)

As Figure 17 shows, in the Baseline condition the parafoveal and post-boundary words were identical so no boundary change was implemented in this condition and the post-boundary word was presented throughout the entire trial. Both the Control and Repeated conditions contained an invisible boundary, and prior to the eyes crossing the boundary alternative parafoveal words were presented at the post-boundary location. In the Repeated condition this parafoveal word was a repetition of the target word itself. In contrast, the parafoveal word in the Control condition was a four- or five-letter word of similar frequency to the pre-boundary word (maximum difference of eight counts per million) that contained none of the same letters as the target word. The control parafoveal word was also of the same word type as the target word.

Apparatus

The participants' eye-movements were recorded using an SR Research Eyelink II head-mounted video-based eye-tracker. They were seated approximately 75 cm away from a 22" Iiyama Vision Master Pro 514 display screen with a resolution of 1024 x 768 pixels. The screen refresh rate was set to 120 Hz so that one screen refresh took 8 msecs, with 16 bits per pixel to increase refresh reliability. Viewing was binocular to assist normal viewing conditions but recording was of the right eye only.

Procedure

At the start of the experiment each participant was fitted with the head-mounted eye-tracker. The position of gaze was tracked using the centre of the pupil as a guide to fixation. The picture of the right eye was calibrated using a nine-point calibration grid with the fixation positions presented in a random order. If the experimenter deemed that the fixation grid produced sufficiently matched the calibration grid then validation was carried out to check the accuracy of the initial fixations. The picture was re-calibrated and validated after the practice sentences, and then after every 10 sentences. This divided the sentences into 13 blocks.

Prior to presentation of the experimental and filler sentences, five practice sentences were presented in order for the participant to familiarise themselves with the procedure. Participants were asked to read each sentence for understanding and answer any questions that followed; they were also asked not to blink or look away from the screen. At the start of each trial a drift correction dot was presented at the centre of the screen, and followed by the sentence. If necessary a drift correction was performed, and if this repeatedly failed to align the eye with the dot a re-calibration was required.

A fixation cross was then flashed onto the screen 40 pixels to the left of the first letter of the sentence for 1000 msecs to ensure that the first fixation on the sentence was following an incoming saccade from the left, as would happen during normal reading. This also ensured that the boundary was unlikely to be crossed without inspection of the preceding text. The sentence was then displayed. Once the eye crossed the invisible boundary (present during the Control and Repeated conditions) the parafoveal word changed to the post-boundary word; if the eye regressed back across the boundary no further display change occurred and the post-boundary word remained. The participant pressed either the Yes or No button on the keypad to end the trial. The procedure was identical for all of the experimental and filler sentences. The order of presentation of the sentences was random.

In order to ensure that the participant was attending to each sentence a comprehension question followed one-third of the sentences. Half of these required a Yes answer and half a No answer, indicated by pressing the relevant keypad button, and were phrased such that a visual inspection of the sentences was not sufficient for an accurate response. To clearly distinguish the comprehension questions from the sentences the questions were written in a normal font rather than the bold font used for the sentences.

The experiment lasted approximately 1 hour. If during the experiment the participant required a break the headset was removed, and the picture was re-calibrated after each break. At the end of the experiment the participant was questioned as to whether they had noticed anything unusual occurring during the experiment such as words changing, and the number of such occurrences reported was noted. Participants were then given de-briefing information.

Data selection

Participants' data were discarded if they did not answer correctly 75% or more of the comprehension questions; no data were discarded under this criterion. They were also discarded if the participant noticed more than about 10% of the changes i.e. 5 out of 46 changes (23 sentences in the Control and Repeated conditions); 6 participants' data were discarded in this manner.

Trials were discarded if the participant reported noticing the boundary change for that trial, if the boundary was triggered by a blink or if the boundary change occurred during a fixation (typically on the boundary itself). This only applied to the Control and Repeated conditions, as there was no boundary change in the Baseline condition. For the Baseline condition trials on which the first-pass scan of the target region was during a blink were discarded. 13% of trials were discarded in these ways.

A word was considered fixated if the eye landed on one of its letters or the space preceding it (Starr & Inhoff, 2004). Fixations less than 50 msecs or greater than 2000 msecs were considered outliers, although no fixations were removed according to this criterion. First-pass measures excluded words that were skipped on first-pass, or fixations prior to or after regressions (Kliegl et al., 2006). This ensured that the only fixations retained for analysis were in a forward direction. Only first-pass measures were of interest as once the gaze moved on to the next word it would cross the invisible boundary and the parafoveal word would be replaced by the post-boundary word, thus eliminating any possible parafoveal-on-foveal effects. The first-pass measures analysed were first fixation duration, gaze duration and fixation probability. First fixation duration is defined as the length of time of the first fixation that lands on a word and gaze duration is defined as the sum of the durations of all the first-pass fixations (e.g., Starr & Rayner, 2001). The measure of fixation probability was calculated as the number of fixations divided by the total number of words in each condition: 23 for the participants analysis and 10 for the items analysis.

Results

Parafoveal preview analysis

The first analysis carried out was of fixations on the post-boundary word to check that a standard parafoveal preview effect was obtained. As Table 3 and Figure 18 show, first fixation durations on word n+1 were longer in the Control and Repeated preview conditions.

Table 3

Mean first fixation durations (and standard deviations) on the post-boundary word in milliseconds as a function of parafoveal preview condition

Parafoveal preview condition		
Baseline	Control	Repeated
236.0 (29.7)	277.8 (39.0)	289.0 (51.1)

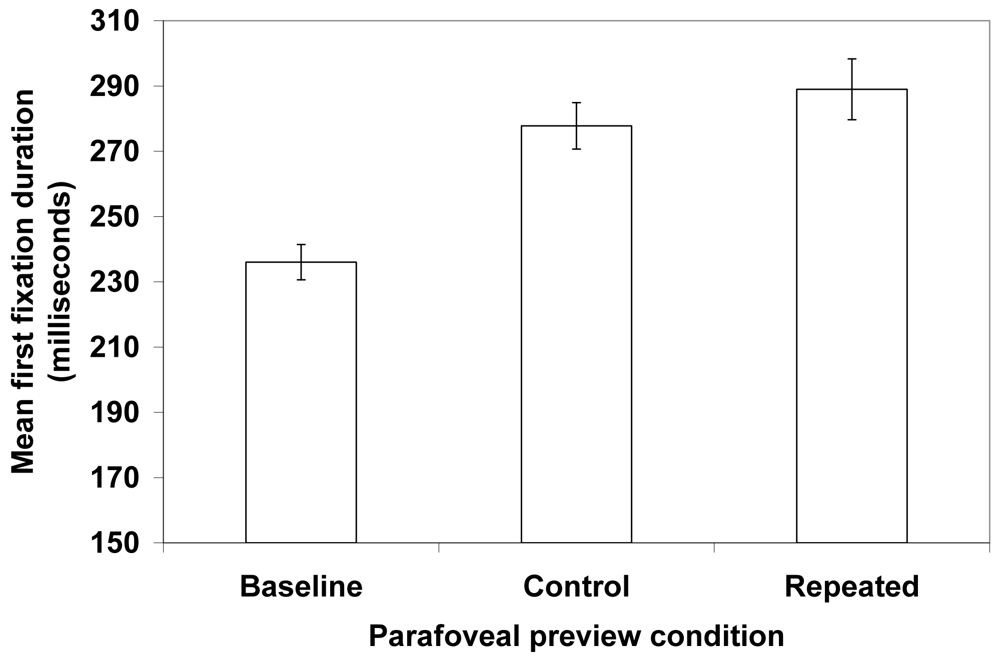

FIG. 18. The effect of parafoveal preview condition on mean first fixation durations on the post-boundary word; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA showed that there was a main effect of preview condition [$F_1(2,58) = 25.83$, $p < 0.001$; $F_2(2,134) = 40.29$, $p < 0.001$], with post-hoc paired-samples t-tests with a Bonferroni correction showing that durations were significantly longer in the Control and Repeated conditions than in the Baseline condition (Baseline-Control [$t_1(29) = 6.97$, $p < 0.001$; $t_2(67) = 7.44$, $p < 0.001$]; Baseline-Repeated [$t_1(29) = 5.86$, $p < 0.001$; $t_2(67) = 8.70$, $p < 0.001$]). There was no significant difference between the Control and Repeated conditions. A linear mixed-effects analysis confirmed these results ([$F(2,1283.72) = 46.28$, $p < 0.001$]; Baseline-Control [$t(1279.70) = 7.40$, $p < 0.001$]; Baseline-Repeated [$t(1288.24) = 8.82$, $p < 0.001$]).

Table 4 and Figure 19 show that similar effects were found in the gaze duration analysis.

Table 4

Mean gaze durations (and standard deviations) in milliseconds as a function of parafoveal preview condition

Parafoveal preview condition		
Baseline	Control	Repeated
262.4 (39.0)	312.4 (57.4)	318.3 (62.0)

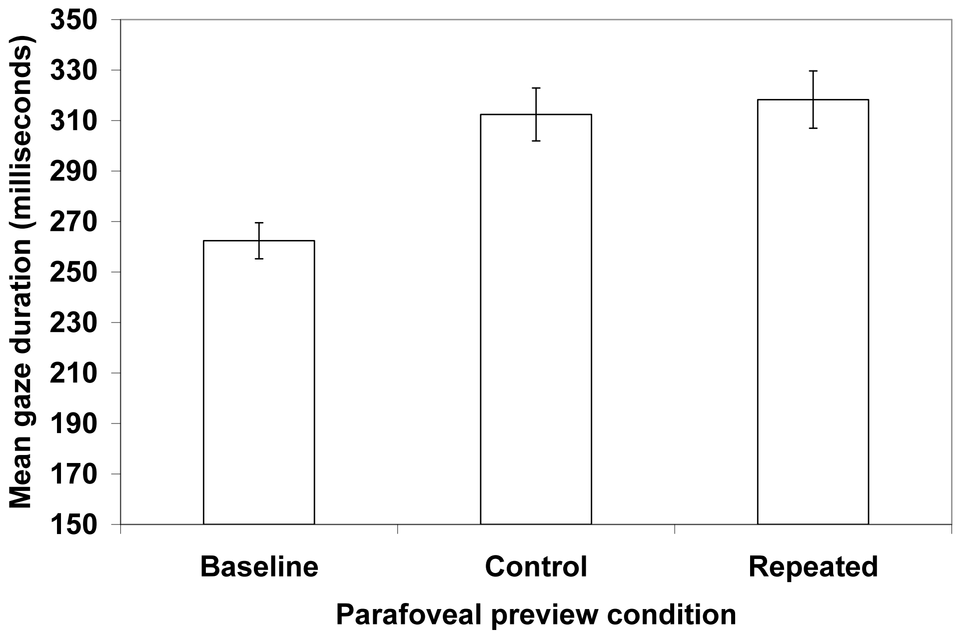

FIG. 19. The effect of parafoveal preview condition on mean gaze durations; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA showed that there was a main effect of preview condition [$F_1(2,58) = 24.33$, $p < 0.001$; $F_2(2,134) = 37.07$, $p < 0.001$], with post-hoc paired-samples t-tests with a Bonferroni correction showing that durations were significantly longer in the Control and Repeated conditions than in the Baseline condition (Baseline-Control [$t_1(29) = 6.39$, $p < 0.001$; $t_2(67) = 7.10$, $p < 0.001$]; Baseline-Repeated [$t_1(29) = 5.51$, $p < 0.001$; $t_2(67) = 8.88$, $p < 0.001$]). A linear mixed-effects analysis confirmed these results ([$F(2,1276.15) = 36.54$, $p < 0.001$]; Baseline-

Control [$t(1272.52) = 7.05$, $p < 0.001$]; Baseline-Repeated [$t(1280.11) = 7.49$, $p < 0.001$]).

In summary, these results are in line with standard findings from parafoveal preview work showing that when an upcoming word is replaced with a different word prior to fixation then this denial of parafoveal preview increases resulting fixation times on that word.

Parafoveal-on-foveal analysis

The main analysis of interest for this experiment was of fixations on the target word. As Table 5 and Figure 20 show, first fixations durations were longest in the Control condition and shortest in the Repeated condition.

Table 5

Mean first fixation durations (and standard deviations) in milliseconds as a function of parafoveal word condition

Parafoveal word condition		
Baseline	Control	Repeated
230.3 (19.9)	236.4 (29.2)	224.1 (26.2)

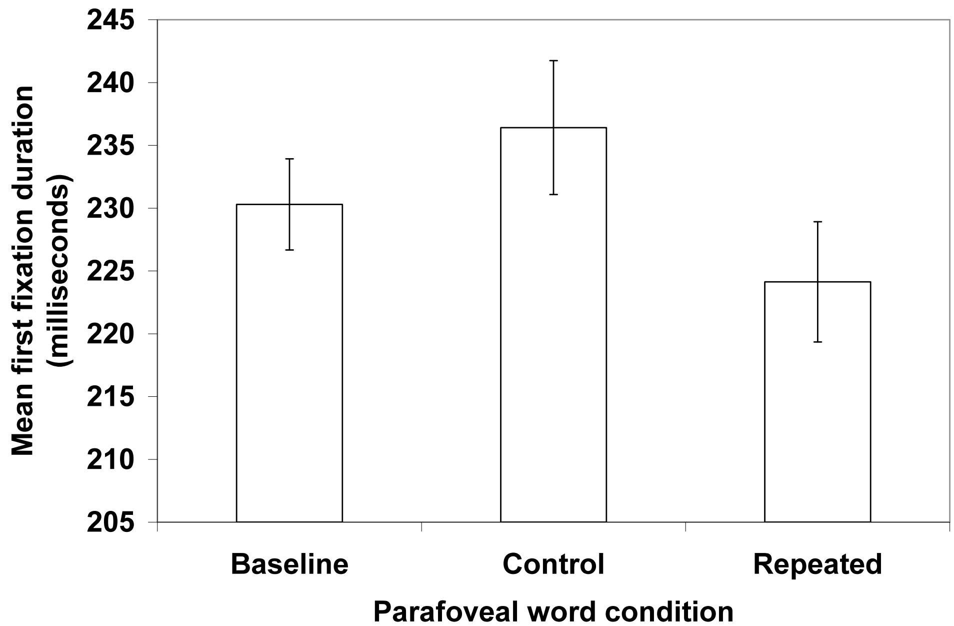

FIG. 20. The effect of parafoveal word condition on mean first fixation durations; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA showed that there was a main effect of parafoveal word condition by participants [$F_1(2,58) = 4.53$, $p < 0.001$], although this was not significant in the items analysis [$F_2(2,136) = 2.26$, *ns*]. Similarly, post-hoc paired-samples t-tests with a Bonferroni correction showed that fixation durations in the Repeated condition were significantly shorter than those in the Control condition in the participants analysis [$t_1(29) = 2.90$, $p < 0.05$], although again this was not true in the items analysis [$t_2(68) = 1.84$, *ns*]. This disparity between the results makes them difficult to interpret, and highlights the need for a more inclusive test such as LME modelling to give an indication of the overall results for the whole data set. In this case the LME analysis showed that there was a significant main effect of parafoveal word condition [$F(2,1348.32) = 4.01$, $p < 0.05$] with the Repeated condition producing significantly shorter first fixation durations than the Control condition [$t(1352.17) = 2.82$, $p < 0.05$].

A similar pattern is indicated by Table 6 and Figure 21 for gaze duration.

Table 6

Mean gaze durations (and standard deviations) in milliseconds as a function of parafoveal word condition

Parafoveal word condition		
Baseline	Control	Repeated
247.1 (30.9)	253.9 (44.3)	235.9 (31.2)

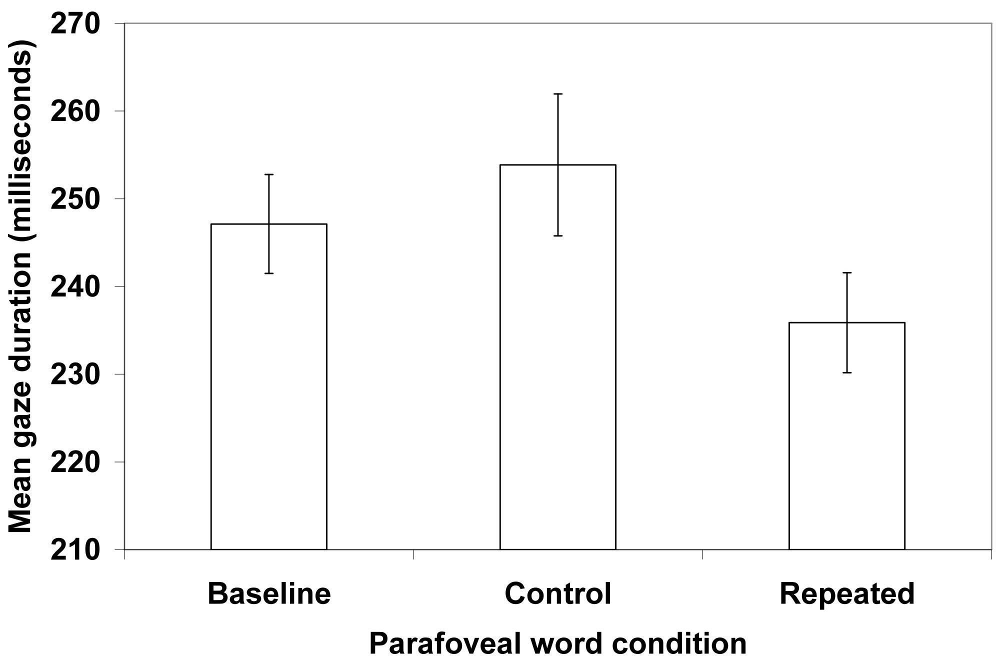

FIG. 21. The effect of parafoveal word condition on mean gaze durations; error bars indicate standard error of the mean

The results for the gaze duration analysis were more clear-cut, with a one-way repeated-measures ANOVA showing that there was a main effect of parafoveal word condition [$F_1(2,58) = 5.49$, $p < 0.001$; $F_2(2,136) = 3.65$, $p < 0.05$]. Again, the Repeated condition produced significantly shorter fixation durations than the Control condition [$t_1(29) = 3.18$, $p < 0.05$; $t_2(68) = 2.68$, $p < 0.05$], with both results supported by LME analyses [$F(2,1347.83) = 4.89$, $p < 0.05$]; [$t(1351.87) = 3.13$, $p < 0.05$].

These results indicate a clear parafoveal-on-foveal effect of priming from a repeated parafoveal word reducing fixation durations on the foveal word. The results appear to indicate that a semantically inappropriate word presented in the parafovea is not detrimental to the processing of the current word if the parafoveal word is a repetition of the foveal word. These results replicate the finding from Chapter 3 that processing of the current word is speeded up by presentation of related letters in parafoveal vision compared to when unrelated letters are presented.

Fixation probability results

The experimental procedure implemented for this experiment did not allow for a full analysis of the effect of parafoveal word condition on the likelihood of fixating the target and post-boundary words. This was due to the absence of the invisible boundary in the Baseline condition meaning that fewer trials in this condition were discarded during data selection than in the Control and Repeated conditions (see Data Selection on page 105). This artificially increased the fixation probability in this condition. Instead, the analysis was limited to a comparison of the Control and Repeated conditions only, firstly for the post-boundary word and then for the target word, as an exploratory assessment of any differences in fixation pattern between the two conditions.

As Table 7 shows, the fixation probabilities on the post-boundary word were similar in the Control and Repeated conditions. A paired-samples t-test showed that there was no significant difference between these fixation probabilities [$t_1(29) = 0.82$, *ns*; $t_2(68) = 0.74$, *ns*].

Table 7

Mean fixation probabilities (and standard deviations) as a function of parafoveal preview condition

Parafoveal preview condition	
Control	Repeated
0.74 (0.12)	0.73 (0.15)

Similarly, the fixation probabilities on the target word in the Control and Repeated conditions were not significantly different from each other [$t_1(29) = 0.06$, *ns*; $t_2(68) = 0.05$, *ns*], as suggested in Table 8.

Table 8

Mean fixation probabilities (and standard deviations) as a function of parafoveal word condition

Parafoveal word condition	
Control	Repeated
0.70 (0.12)	0.70 (0.13)

Discussion

Parafoveal preview predictions

This experiment recorded the eye movements of 36 participants while reading a series of sentences containing a target word followed by an invisible boundary. The word following the boundary was either a repetition of the target word or orthographically unrelated to it, and once the boundary was crossed this word was replaced by another more semantically appropriate to the sentence. The first set of analyses that were carried out on these data covered the responses to the post-boundary word in the Repeated, Control or Baseline condition involving no boundary change. This was to assess any parafoveal preview benefit accrued on the post-boundary word in the Baseline condition, which was the only condition in which the post-boundary word was available for pre-processing prior to fixation. In line with multiple previous findings, the prediction was that first-pass fixation durations would be reduced in the Baseline condition compared to the Repeated and Control conditions.

Confirming this prediction, a standard parafoveal preview benefit for the post-boundary word was obtained: first fixation and gaze durations were significantly shorter in the Baseline condition than in the Repeated and Control conditions. There was no difference between the Repeated and Control conditions on these measures. This confirms the similarity of this experiment with previous work in this area (see Rayner, 1998, for a review).

Parafoveal-on-foveal predictions

The focus of this experiment was not on the nature of parafoveal preview benefit but rather on the potential demonstration of parafoveal-on-foveal effects. Specifically, if word n+1 is processed concurrently with word n then an orthographically related post-boundary word (Repeated condition) should reduce fixation durations on the pre-boundary target word, compared with when an orthographically dissimilar word is presented (Control condition). Orthographic priming is well-documented in both the isolated word and text reading literature (e.g., Forster & Davis, 1984; Inhoff, Radach, et al., 2000), although not in sentence reading with an invisible boundary. Any finding of parafoveal-on-foveal influences provides firm support for models involving parallel processing of adjacent (e.g., SWIFT, Engbert et al., 2002; Glenmore, Reilly & Radach, 2003).

This prediction of orthographic priming from a repeated word was supported by the finding that both first fixation durations and gaze durations on the pre-boundary word were significantly shorter in the Repeated condition than in the Control condition. The post-boundary words in the two conditions were equated on length, frequency and approximate word type, and neither formed plausible continuations of the pre-boundary sentence, so it seems safe to conclude that their differing effects were due to their differing levels of orthographic similarity to the pre-boundary word. However, neither of these conditions was significantly different from the Baseline condition on either variable. This does not support the prediction that the Repeated condition would produce shorter pre-boundary fixation durations than the Baseline condition. This stronger prediction was based on the work by Inhoff, Radach, et al. (2000) who found reduced fixation durations on a target word when the post-target word was identical compared to a baseline word. Upon reflection it is perhaps unsurprising that this difference failed to materialise in this experiment: the sentences presented by Inhoff, Radach, et al. did not contain an invisible boundary and the repeated word was available for foveal inspection. This overt presentation might have induced strategic reading as participants were almost certainly aware that repeated words were a feature of the experiment. In contrast, the current experiment was defined by the covert presentation of a repeated word, hence the use of the boundary paradigm. Additionally, a comparison between the Repeated and Control conditions is probably more suitable as the letter overlap between the parafoveal words in these conditions was controlled, unlike in the Baseline condition. The target words in the Repeated and Control conditions were also both semantically anomalous.

As discussed in the Results section a full analysis of the fixation probability data across all three conditions was not possible, but the results for fixation probability for both the post-boundary and pre-boundary words in the Repeated and Control conditions indicate no significant differences between them. This follows the pattern of results for parafoveal preview benefit but not for parafoveal-on-foveal priming. Given the clear-cut results outlined above for the pre-boundary word this result suggests that fixation probability might not be a suitable indicator of orthographic priming effects, rather than implying that they do not occur. This is analogous to the results from the Orthographic FLLD task which showed that lexical decision reaction time, and not decision accuracy, was an indicator of parafoveal orthographic priming. In both cases, priming was manifested in the response times. In order to complete a full fixation probability analysis in future experiments an invisible boundary will be implemented in all three conditions to equate the number of responses removed due to artefactual boundary triggers.

Implications for models of eye movement control during text reading

The parafoveal-on-foveal orthographic priming demonstrated in this experiment suggests that adjacent words are processed simultaneously during text reading and adds to the substantial and increasing body of work implying parallel word processing (e.g., Kennedy et al., 2002; Kliegl et al., 2006). This work provides the impetus for models such as SWIFT (Engbert et al., 2002) and Glenmore (Reilly & Radach, 2003) which model attention as a gradient spread over multiple words. This is the first demonstration of parafoveal-on-foveal orthographic priming in sentences without reliance upon overt repetition of the target word (see Inhoff, Radach, et al., 2000, and Vitu et al., 2004, for comparison). There are, however, several criticisms that could be levelled at this work that will be discussed below.

A previously stated criticism from Rayner and colleagues (e.g., Rayner, Juhasz, et al., 2007) is that parafoveal-on-foveal influences could be ascribed to mislocated fixations that were intended for word n+1 but that actually fall on word n. Thus, although the fixation is recorded as foveal it is the parafoveal word that is attended to and processed and whose properties affect the characteristics of the fixation. This theory predicts that parafoveal-on-foveal effects should therefore only be observed for fixations that fall close to the parafoveal word as these are more likely to be mislocated. Inhoff, Radach, et al. (2000) tested this theory by comparing the analyses for fixations that fell either more or less than four characters from the parafoveal word, and found no difference. Similar separate analyses were not possible in the current work as the pre-boundary words were either four or five letters in length.

Several previous studies researching orthographic parafoveal-on-foveal effects (e.g., Inhoff, Starr, et al., 2000; Pynte et al., 2004; Starr & Inhoff, 2004) have used parafoveal words containing illegal or unusual orthography, such as typos or nonwords. The criticism of the high visual saliency of these manipulations (Rayner, White, et al., 2003) does not apply to the current experiment which included only lexical items and took advantage of the boundary paradigm to ensure that the repeated word was only available in parafoveal vision. To further ensure that the participants' reading strategy was geared towards sentence comprehension and was not affected by the experimental procedure, comprehension questions were presented and upon completion of the experiment participants were questioned as to the number of word changes (if any) that they had perceived. The data from participants who did not correctly answer sufficient questions or who noticed multiple changes during the course of the experiment were discarded.

The final potential criticism of this work is that the priming from word n+1 could be due to purely visual similarity between word n+1 and word n, rather than orthographic effects. In the early versions of E-Z Reader (Reichle et al., 1998; 1999) even low-level parafoveal-on-foveal effects were problematic as all processing was considered to be serial in nature. However, Rayner and colleagues (Pollatsek et al., 2006; Reichle et al., 2003; 2006) later amended the model to include a pre-attentive visual stage that operates in parallel across the visual field and acquires information about word boundaries and letter shapes that segments the upcoming text into word objects; the authors have explicitly stated that this stage allows E-Z Reader to account for parafoveal-on-foveal effects of unusual orthography (e.g., Rayner, Juhasz, et al., 2007). Although this pre-attentive stage has a fixed duration of 50 milliseconds, presumably the illegal orthography of the parafoveal word acts to alter the duration of the L1 stage of lexical processing for the fixated word and the initiation of an eye movement to the parafoveal word. The details of this process are not elucidated, and Rayner and colleagues do not address the findings of Inhoff, Radach, et al. (2000) or Vitu et al. (2004) to explain how orthographic priming effects might occur in the absence of attention. Nevertheless, if the results of the current experiment are due to visual similarity between the foveal and parafoveal words rather than orthographic priming (which cannot be determined with the current stimuli) then this parallel pre-attentive stage could presumably be extended to account for these as well. Chapter 6 will return to this topic, but in the meantime to provide further evidence for the debate about how attention is allocated during reading the next experiment turns to the possibility of parafoveal-on-foveal effects from word n-1, an effect very clearly predicted by models of parallel processing only.

Chapter 5
The Repeated Word n-1 Parafoveal-on-Foveal Task
Introduction

Aims of the chapter

Chapter 4 of this thesis has provided a clear demonstration that orthographic priming from word n+1 reduces fixation durations on word n in a naturalistic reading task. While this strongly suggests that word processing occurs in parallel across multiple words and provides support for models such as SWIFT (Engbert et al., 2002), advocates of serial processing styles have suggested that parallel orthographic processing could occur even within a serial lexical framework. For example, E-Z Reader versions 7+ (Reichle et al., 2003) implement a parallel pre-attentive visual processing stage that occurs prior to a serial shift of attention initiating lexical processing, and although not fully explained it is conceivable that orthographic priming effects could take place within this mechanism. Aside from the issue of serial and parallel processing there are other related factors that distinguish these two models: one of these is their characterisation of the perceptual span, with SWIFT describing information uptake as commonly occurring over a larger area than E-Z Reader, including to the left of fixation. This chapter therefore details a further orthographic priming experiment that instead relies on repetition of word n-1.

The perceptual span

The perceptual span refers to the area from which we are able to obtain visual useful information to aid the reading process during a single fixation (e.g., Rayner & Juhasz, 2006). Acuity constraints clearly limit this span, as beyond approximately 5° from the centre of fixation text falls outside parafoveal vision. However, simple demonstrations that we process information from not only the current word but the surrounding ones as well are the finding that we are more likely to skip predictable words than unpredictable words (e.g., Rayner & Well, 1996), and the fact that reading times increase by approximately one-third when parafoveal information is denied (Rayner, Well, Pollatsek, & Bertera, 1982). These findings suggest that during a fixation we both inspect information outside the current word and that any information received is integrated into the reading system to inform later eye movement behaviour.

Analysis of the exact size of the perceptual span and the types of information that are extracted away from foveal vision have been the subject of a large body of research. Early work involved the use of the moving window technique (McConkie & Rayner, 1975). This is an eye movement contingent paradigm in which there is a window of text around the participant's fixation point. Outside this window the text is rendered uninformative, typically by replacing all of the letters with X's. The minimum size of the window that can be presented without disrupting reading indicates the size of the effective perceptual span. Initial work using a symmetrical window indicated a span of approximately 14 characters to either side of fixation (Den Buurman, Boersema, & Gerrissen, 1981; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner et al, 1982).

The processing of word n-1

However, researchers who varied the symmetry of the moving window found that the perceptual span is about 14 characters in the direction of reading but only about 4 characters in the opposite direction (e.g., McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). Underwood and McConkie (1985) found that the processing of letter information is restricted to a smaller area of 4 letters to the left and 8 letters to the right of fixation, and concluded that any processing outside this smaller window is of low-level cues such as word shape. The opposite direction of the asymmetry of the minimal window for Hebrew and English showed that it is due to attentional direction rather than cerebral lateralisation (Pollatsek, Bolozky, Well, & Rayner, 1981). Experimental manipulation of attention by Rayner et al. (1978) suggested that attention modulates the perceptual span to the extent that there is little processing of information that lies in the opposite direction from reading. They used an offline isolated word parafoveal preview task in which participants were cued to name one of the words presented either side of a fixation point. They found that having a related preview prime on the opposite side to the way the eyes moved provided no benefit over presenting an unrelated preview. Rayner, Well, et al. (1980) concluded that the window in the opposite direction from reading simply had to fully incorporate the currently fixated word for reading to be normal. In other words, in a left-to-right reading language no information is extracted from the words to the left of fixation.

Research on the information extracted to the left of fixation has also been carried out using the boundary paradigm (Rayner, 1975) that is commonly used in experiments showing that information gained from a parafoveal word serves to reduce the processing load of that word when it is subsequently fixated. The parafoveal word under consideration is typically to the right of the boundary, hence the name parafoveal preview for the type of processing benefit described above, but some work has also been carried out looking at parafoveal postview effects as it is possible that the moving window paradigm is too insensitive to detect subtle effects (Binder et al., 1999). There was a suggestion of a parafoveal postview effect in work by Balota et al. (1985) in the specialised case of skipping of post-boundary words. When the post-boundary word was skipped following a boundary change (so the post-boundary word was neither fixated nor previewed) there were more regressions back to the post-boundary word than when the post-boundary word was skipped when no boundary change occurred (so the post-boundary word was previewed).

Binder et al. (1999) acknowledged that this was a limited effect and in their replication of this work they included a postview condition in which the boundary change occurred to the left of the post-target word and only after it was fixated. The target word was replaced with either a contextually consistent or unrelated word (see Figure 22). Although the postview change did not affect post-target word reading, less time was spent re-reading the target word when its postview replacement was consistent than unrelated. This again suggests that some processing of the word to the left of fixation might take place.

```
...before he's had his morning coffee| and read...
                                  *  |
...before he's had his morning shower| and read...
                                     |  *    (consistent)
...before he's had his morning carpet| and read...
                                     |  *     (unrelated)
...before he's had his morning coffee| and read...
                                  *  |
```

FIG. 22: Two different parafoveal postview conditions and the post-boundary presentation of the target word *coffee* in the work by Binder et al. (1999) (the dashed line indicates the position of the invisible boundary; the asterisks indicate the position of the eyes)

The perceptual span and reading models

The issue of whether the perceptual span extends to the left of the currently fixated word, whether a regression is executed or not, is one of the factors that separates serial and parallel processing models of eye movement control during text reading. As an example of the former processing style, E-Z Reader (Reichle et al., 1998) implements an attention-shift mechanism that allocates attention to one word at a time and that initially does not appear to allow for lexical information to be retrieved from the words to the left of fixation. In contrast, an example of the latter category SWIFT (Engbert et al., 2002) relies upon a gradient of attention simultaneously activated across multiple words, including the word to the left of fixation. However, the findings by Binder et al. (1999) and Balota et al. (1985) can be explained by E-Z Reader with its de-coupling of attention from eye movements. Lexical information from word n-1 can be obtained if the eyes moved to word n before the corresponding shift of attention. If word n-1 changed during this attentional lag this would prompt a re-reading of word n-1; this explains why the only effect of changing word n-1 was to increase target regressions or re-reading durations.

The above explanation implies that processing of word n-1 is an anomaly revealed in an unusual eye movement pattern, rather than a common part of the reading strategy. Inhoff, Radach, et al. (2000) suggested the complementary use of a word-processing task to determine whether this implication is correct. They also employed a parafoveal postview paradigm like that in Figure 22, with the word to the left of the boundary replaced with a contextually consistent word. Following sentence reading participants engaged in a forced-choice decision as to which of three words was presented in the previous sentence. These three words were the original pre-boundary word, the contextually consistent replacement word, and a word that never appeared in the sentence. While the original word was the most likely to be chosen, the replacement word that had only ever been presented to the left of fixation was chosen significantly more often than the new word; this occurred irrespective of target re-reading. The possibility that this outcome could have been due to the contextual consistency of the replacement word was removed in a follow-up experiment with no boundary change. The selection rate for the replacement word was significantly higher in the first experiment than in the second, although this involved a weak between-experiments comparison and the authors do not report whether the selection rate for the replacement word was still significantly higher than for the new word in the second experiment. These forced-choice results led them to suggest than any word within effective visual range can undergo simultaneous lexical analysis. They proposed a gradient of attention allocation across the continuous visual array, with a higher gradient value being assigned to fixated words and words that prove difficult to recognise.

This attention-gradient hypothesis finds its formal implementation in SWIFT, in a dynamical field approach that involves spatially distributed processing across multiple words. This approach is supported by several recent studies analysing data from both corpora and experiments. Kliegl and colleagues (Kliegl, 2007; Kliegl et al., 2006) carried out a large-scale study of single sentence reading by hundreds of participants. They presented evidence that processing of word n-1 continues during fixation on word n and affects fixation durations on it: word length, frequency and predictability of word n-1 all contributed to this cognitive lag. Similarly, Pynte and Kennedy (2006) analysed the eye movement patterns recorded from English and French corpora and included both standard independent variables of n, n+1 and n-1 word length, frequency and initial trigram informativeness, and non-standard variables such as the length of words n-4...n-10 and the rank position of the word in the sentence. They found an increase in the first fixation duration and gaze duration on word n as the length of word n-1 increased.

Although these corpus studies are suggestive, they cannot rule out the possibility that while lexical processing of word n-1 extends into subsequent fixations, this is prior to rather than concurrent with lexical processing of word n. For this we must turn to experimental studies that present novel stimuli at position word n-1 during fixation on word n. The work of most interest in the current context of experimental parafoveal-on-foveal influences is that of Starr and Inhoff (2004). In the second of two experiments they presented sentences containing a parafoveal postview boundary such as that shown in Figure 23 with the intention of assessing whether an orthographically illegal nonword presented at position n-1 would influence target viewing durations in a backwards parafoveal-on-foveal effect. In line with their previous parafoveal-on-foveal findings (Inhoff, Starr, et al., 2000; Starr & Inhoff, 2004, experiment 1) they predicted that if attention is spread across multiple words, including the word to the left of fixation, then fixation durations on the target word should increase in the presence of an orthographically illegal nonword. They found a small but reliable effect (by participants only) of word n-1 condition on first fixation and gaze durations on the post-boundary target word, a finding difficult to reconcile with a serial processing model.

The current experiment

This experiment follows on from the findings of the Repeated Word n+1 Parafoveal-on-Foveal task by presenting the repeated word (and orthographically unrelated control) to the left of the target word following a boundary change. A meaningful sentence was presented until the pre-target boundary was crossed and the target word fixated, at which point the experimental parafoveal word was presented at position n-1. There were again three parafoveal word conditions: Baseline (semantically appropriate word presented throughout); Repeated (target word repeated in position n-1); and Control (word orthographically unrelated to the target word presented in position n-1). As in the previous experiment, in the Baseline condition the parafoveal word did not change.

```
The store had a coat| sale that week  (pre-boundary)
                 *  |
The store had a sale| sale that week     (Repeated)
                    |  *
The store had a inch| sale that week      (Control)
                    |  *
The store had a coat| sale that week     (Baseline)
                    |  *
```

FIG. 23: The three word n-1 conditions (the pre-boundary and target words are italicised, the dashed line indicates the position of the invisible boundary and the asterisks indicate the position of the eyes)

Predictions

Given the orthographic priming demonstrated in the previous two experiments, the prediction for this experiment is that first-pass fixation durations on the target word will be reduced in the Repeated condition due to orthographic priming from the repeated target word. As the experimental manipulation only occurs after the target word is fixated fixation probability is no longer of interest, but the exploratory variable of number of regressions to the pre-boundary word will be added. One caveat is that any effects are likely to be reduced in size compared to the word n+1 orthographic priming results: as the work by Starr and Inhoff (2004) demonstrates, learned direction of reading 'pulls' attention to the right of the fixated word leading to smaller effects of word n-1. The fact that the experimental words are only presented during first-pass fixations on the target word (rather than for the entire duration of the sentence presentation until the boundary is crossed, as was the case in the previous experiment) is likely to reduce any effects still further. Lastly, there can be no parafoveal preview analysis with this paradigm as the post-boundary word is not altered.

Method

Participants

30 students from the University of Edinburgh took part and were paid £10 for their participation. They were all native English speakers with no language disorders and normal or corrected-to-normal vision. None had participated in the Word n+1 eye-tracking experiment.

Design

The independent variable in this experiment was the identity of word n-1 following a boundary change. It had three levels: Baseline (word n-1 unchanged), Control (word n-1 unrelated) and Repeated (word n-1 repeated). There were 69 experimental sentences. The three conditions were counterbalanced across participants and items such that 23 sentences were presented in each condition across three versions of the experiment. 10 participants were assigned to each version.

Materials

The materials used were similar to those used in the Word n+1 eye-tracking experiment, consisting of 69 experimental sentences and 50 filler sentences, with 5 practice sentences. Each experimental sentence contained a word pair of a target word matched with a pre-boundary word which was replaced following a boundary change with a parafoveal word that was either identical to the pre-boundary word (Baseline condition), identical to the target word (Repeated condition) or contained none of the letters of the target word (Control condition). The boundary was located one pixel to the right of the pre-boundary word.

However, given that the word pair had to be part of a meaningful sentence and that the target word was now located to the right of the boundary some of the pre-boundary and target word pairs (and therefore the sentences) were altered slightly in order to meet the same constraints on frequency, word type and length. Even when the sentences did not change, the control parafoveal words were often altered. In this experiment the frequency difference between the target and the pre-boundary words was a maximum of 11 counts per million, and the maximum difference in frequency between the target and control parafoveal words was 10 counts per million. New comprehension questions and filler sentences were constructed where required.

Unlike the Repeated Word Parafoveal-on-Foveal task this experiment required a double boundary change as the parafoveal word was only presented when the eye was to the right of the boundary. In order that participants should not notice the contextual disruption this second boundary change replaced the experimental parafoveal word with the meaningful pre-boundary (Baseline) word if the eyes regressed back to the pre-boundary area. Figure 24 uses the Repeated condition to indicate the sequence of changes over four successive fixations across the boundary. No further changes were initiated, limiting the target word analysis to first-pass measures only. The pre-boundary word was then displayed during the remainder of the trial so there were a maximum of two boundary changes per trial.

```
The store had a coat|sale that week   (pre-boundary)
                 *  |
The store had a sale|sale that week   (Repeated)
                    |  *
The store had a coat|sale that week   (regression)
                 *  |
The store had a coat|sale that week   (second-pass)
                    |  *
```

FIG. 24: The double boundary change that occurred following a regression back across the boundary (the pre-boundary and target words are italicised, the dashed line indicates the position of the invisible boundary and the asterisks indicate the position of the eyes)

Additionally, there was a boundary change in the Baseline condition as well as in the Repeated and Control conditions. In the Word n+1 experiment the boundary had been left out of the Baseline condition as the post-boundary and parafoveal words were identical. However, this meant that the Baseline condition could not be included in the analysis of fixation probability as no trials were excluded due to fixations triggering the boundary in this condition. In order to rectify this problem, and more generally to equate the number of discarded trials across the conditions, a boundary was included in the Baseline condition in this experiment, even though no word replacement occurred.

Apparatus

This was identical to the apparatus used in the Repeated Word n+1 eye-tracking experiment.

Procedure

The procedure was almost identical to that involved in the Repeated Word n+1 eye-tracking experiment. The only difference was that the double boundary system meant that there could be two word changes during the experimental sentences.

Data selection

This was again similar to the data selection procedure carried out in the Repeated Word n+1 eye-tracking experiment, with a few changes. Participants' data were discarded if they did not answer correctly 75% or more of the comprehension questions; one participant's data were discarded under this criterion. They were also discarded if the participant noticed boundary changes in more than about 10% of the trials i.e. 5 out of 46 trials (23 sentences in the Control and Repeated conditions); 13 participants' data were discarded in this manner. This is almost double the number of participants excluded from the Repeated Word n+1 eye-tracking experiment, which is unsurprising given that there were potentially twice as many boundary changes that could occur in this experiment due to the double boundary system. Four participants' data were discarded due to very poor calibration of their eye movements.

Trials were discarded if the participant reported noticing the change for that trial, if the boundary was triggered by a blink or if the boundary change occurred during a fixation (typically on the boundary itself). Unlike in the Word n+1 eye-tracking experiment, this procedure was carried out for all conditions, including the Baseline condition. However, this criterion was only applied to the first boundary change i.e., the change from pre-boundary to parafoveal word. This was for two reasons: the main reason was that only first-pass fixations on the target word were of interest, and even if the second boundary change had occurred during a fixation or a blink it would not have disrupted the first-pass fixation pattern. The minor reason was that it would have meant the loss of more data. Some 22% of trials were discarded in this way.

A word was considered fixated if the eye landed on one of its letters or the space preceding it (Starr & Inhoff, 2004). Fixations less than 50 msecs or greater than 2000 msecs were considered outliers, although no fixations were removed according to this criterion. First-pass measures excluded words that were skipped on first-pass, or fixations prior to or after regressions (Kliegl et al., 2006). This ensured that the only fixations retained for analysis were in a forward direction, and was identical to the data selection method used for Experiment 2. However, the standard procedure of focusing on only those fixations that proceed from left-to-right in a strictly linear manner stems from the use of first-pass fixations by Rayner and colleagues, who consider that regressions are an indicator of processing difficulties for previous text (e.g., Binder et al., 1999). Parallel processing theorists such as Kliegl and colleagues instead characterise attention paid to the left of the fixated word as a normal part of the information gathering and processing pattern, implying that there is useful information for researchers in the previously discarded words whose fixation either follows or precedes a regression. It would be worthwhile for future research on the topic of processing of word n-1 to include an analysis of those discarded words and of the regressions that are made, as it is possible that the regression patterns recorded are more than an anomaly.

First fixation durations, gaze durations and fixation probabilities were calculated. Additionally, the number of regressions back to the pre-boundary word was calculated for each condition. There were two pieces of missing data for the items analysis: there were no fixations recorded by any participants for the item ‘room’ in the Baseline condition for either first fixation or gaze duration.

Results

Parafoveal-on-foveal analysis

Unlike in the Word n+1 eye-tracking experiment no analysis of parafoveal preview effects was carried out for this experiment as the target word was the post-boundary word.

As Table 9 and Figure 25 show, first fixations durations on the target word were very similar in all three conditions.

Table 9

Mean first fixation durations (and standard deviations) in milliseconds as a function of pre-boundary word condition

Pre-boundary word condition		
Baseline	Control	Repeated
235.2 (37.6)	237.1 (36.5)	234.8 (34.4)

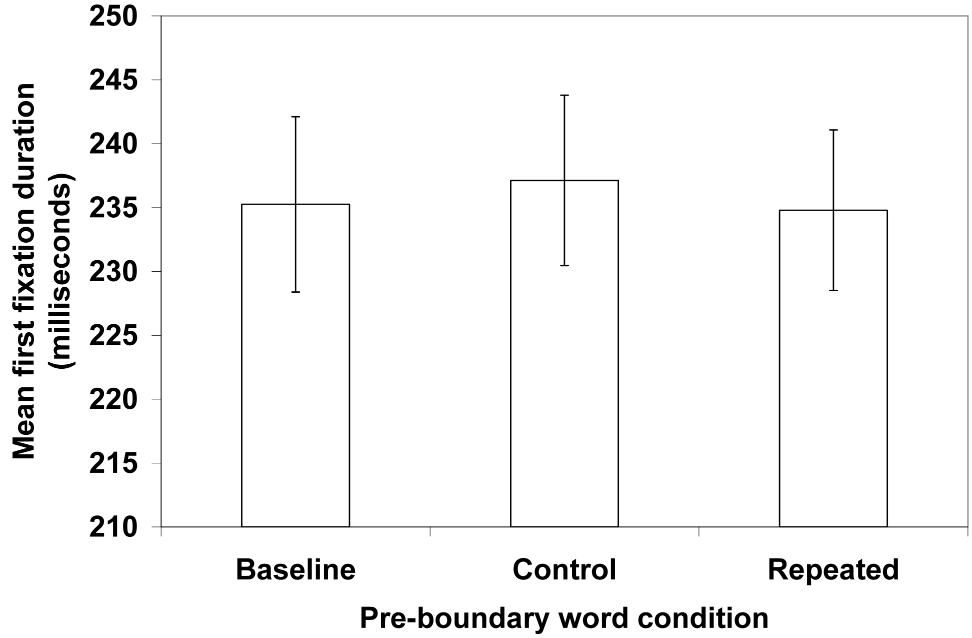

FIG. 25. The effect of pre-boundary word condition on mean first fixation durations; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA showed that there was no main effect of parafoveal word condition [$F_1(2,58) = 0.10$, *ns*; $F_2(2,134) = 0.66$, *ns*]. Similarly, the LME analysis showed that there was no main effect of parafoveal word condition [$F(2,1092.41) = 0.60$, *ns*].

A similar pattern for gaze durations is indicated by Table 10 and Figure 26.

Table 10

Mean gaze durations (and standard deviations) in milliseconds as a function of pre-boundary word condition

Pre-boundary condition		
Baseline	Control	Repeated
245.7 (38.3)	247.8 (39.9)	246.5 (41.1)

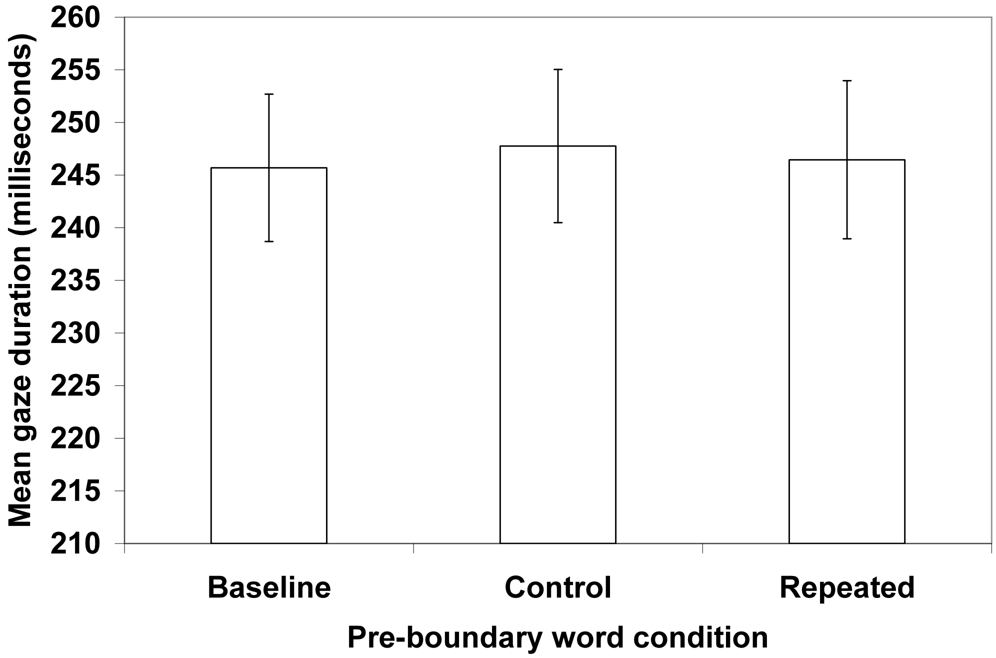

FIG. 26. The effect of pre-boundary word condition on mean gaze durations; error bars indicate standard error of the mean

The results for the gaze duration were the same as those for first fixation duration, with a one-way repeated-measures ANOVA showing that there was no main effect of parafoveal word condition [$F_1(2,58) = 0.04$, *ns*; $F_2(2,134) = 0.59$, *ns*], a result supported by an LME analysis [$F(2,1093.11) = 0.89$, *ns*].

The final dependent variable considered was number of regressions per condition made following first-pass fixations. Table 11 and Figure 27 show that this number was slightly higher for the Control condition than for the Baseline or Repeated conditions.

Table 11

Mean number of regressions (and standard deviations) as a function of pre-boundary word condition

Pre-boundary word condition		
Baseline	Control	Repeated
1.8 (1.8)	2.1 (1.8)	1.9 (1.4)

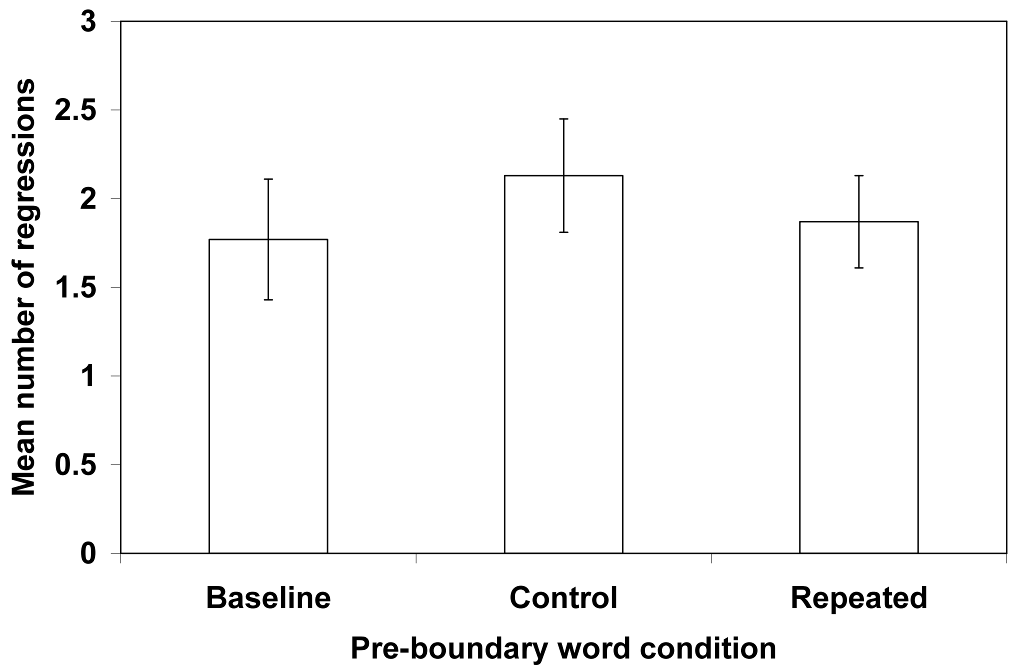

FIG. 27. The effect of pre-boundary word condition on mean number of regressions; error bars indicate standard error of the mean

The slight trend towards more regressions in the Control condition was not borne out in a one-way repeated-measures ANOVA which found no main effect of parafoveal word condition [$F_1(2,58) = 0.56$, *ns*; $F_2(2,136) = 0.85$, *ns*].

Discussion

Predictions

This experiment extended the work on orthographic priming from parafoveal words to the word n-1 position. Thirty-six participants read sentences containing a target word preceded by an invisible boundary, and when the boundary was crossed the pre-boundary word changed to either a repetition of the post-boundary target word or an orthographically unrelated word of the same length and similar lexical frequency. Recording of the eye movement pattern produced during first-pass fixation of the target word allowed investigation of the possibility of an orthographic parafoveal-on-foveal effect from word n-1. This would have provided strong support for parallel reading models such as SWIFT (Engbert et al., 2002) that implement an attentional gradient spread over several words, including the word to the left of fixation.

Contrary to the predictions made and the findings from the previous two experiments, the results of this experiment were all null findings. There were no significant differences recorded between any of the three parafoveal word n-1 conditions in terms of first fixation duration, gaze duration or number of regressions. These results therefore provide no evidence for parafoveal-on-foveal effects from word n-1.

Implications for parallel processing

One of the most contentious areas of research in the recent reading literature is the investigation of parafoveal-on-foveal influences in which the properties of a flanking word affect the processing of the word under fixation. Unsurprisingly, this debate has centred on the effects of the upcoming word rather than the previous one due to work on the perceptual span indicating that it does not extend further to the left than the start of the currently fixated word. The reason for the contention is the assertion by those who advocate models of eye movement control during text reading reliant upon parallel lexical processing (e.g., Engbert et al., 2002) that parafoveal-on-foveal effects could not occur under a serial lexical processing framework (e.g., Drieghe et al., 2005). However, recent versions of the most well-specified serial processing model E-Z Reader (Pollatsek et al., 2006; Reichle et al., 2006; Reichle, Pollatsek, & Rayner, 2007) can account for at least sub-lexical parafoveal-on-foveal effects such as those due to illegal orthography (Inhoff, Starr, et al., 2000; Starr & Inhoff, 2004).

In contrast, parafoveal-on-foveal influences from the left of fixation are a critical test of serial processing, as in E-Z Reader (e.g., Reichle et al., 1998) there is no useful information extracted from word n-1 during fixation on word n, except in the special case of the eyes shifting to word n before lexical processing of word n-1 was complete; this would only be manifested in the re-reading of word n-1 (Binder et al., 1999). Under an E-Z Reader framework the attentional demands of word n preclude any lexical processing of word n-1. However, several studies have shown that information uptake from word n-1 can occur without re-reading (Inhoff, Radach, et al., 2000; Starr & Inhoff, 2004) and that processing of word n-1 during fixation on word n routinely occurs during normal reading (Kliegl, 2007; Kliegl et al., 2006, Pynte & Kennedy, 2005).

The finding of orthographic priming from word n-1 speeding up fixations on word n would have added to the support for parallel processing models, but as discussed above no trace of priming was demonstrated in the results of this experiment, instead lending support to serial models such as E-Z Reader. However, a null finding is less satisfactory than a positive result and it is difficult to make conclusive statements in this situation. While an orthographic-level parafoveal-on-foveal effect from word n-1 would have been strong evidence in favour of parallel processing the absence of an effect does not rule out the possibility that there is uptake of information from word n-1 during fixation on word n, but rather that this experiment did not demonstrate it. As mentioned in the Introduction, reading direction and the limited presentation duration of the parafoveal word were predicted to attenuate any priming effects and they could have been responsible for masking a subtle effect. As Inhoff, Radach, et al. (2000) discussed, the eye movement pattern might not be the optimal record of word n-1 processing and researchers might be advised to take this into consideration when designing future experiments.

Future work

The final eye-tracking experiment in this thesis will therefore return to more straightforward word n+1 parafoveal-on-foveal effects in text reading. As mentioned in Chapter 4, the finding that, if word n+1 is a repetition of word n, processing time on word n is reduced could potentially be explained in a serial model such as E-Z Reader with the inclusion of a parallel pre-attentive visual scanning stage. If the parafoveal priming observed was due to visual rather than orthographic similarity a parallel visual stage could accommodate this effect. Chapter 6 therefore presents an experiment designed to separately manipulate the orthographic and visual relationship between the parafoveal and foveal words. This manipulation also has the advantage of mimicking a subtle orthographic processing paradigm that has been utilised in the isolated word literature to distinguish between two major classes of word recognition model, allowing the upcoming experiment to act as a test of which style of word recognition is most appropriate in text reading.

Chapter 6
The Transposed Letters Parafoveal-on-Foveal Task
Introduction

Aims of the chapter

This chapter has two aims: to provide evidence in favour of orthographic parafoveal-on-foveal effects, and to continue the fledgling discussion of which class of model of word recognition is most appropriate in text reading. The following experiment is based on the work by Johnson et al. (2007) that addresses both of these topics using a parafoveal preview paradigm that will be adapted to a parafoveal-on-foveal priming experiment in the manner of the previous two experiments. Johnson et al.'s work used transposed-letters priming to attempt to ascertain whether slot-based input letter coding is appropriate in a model of text reading and touches on the more general question of the relative importance of letter identity and position in word identification. The current experiment focuses on the same questions and extends the Repeated Word parafoveal-on-foveal task introduced in Chapter 4 with the addition of a comparison between transposed-letters and substituted-letters parafoveal primes. This has the added advantage of providing a test for orthographic, rather than visual, parafoveal-on-foveal effects, which will also be explored in this chapter.

Orthographic parafoveal-on-foveal effects

As mentioned in Chapter 4, the finding that repeating word n in the word n+1 position decreases fixation durations on word n compared to an orthographically unrelated word n+1 word strongly implies that this is an orthographic parafoveal-on-foveal effect, a finding that runs counter to the predictions of serial attention shift models such as E-Z Reader (Reichle et al., 1998). However, this effect could be visual in nature rather than orthographic, and as such could be explained by the recent addition of a parallel pre-attentive visual scanning mechanism to the model (Reichle et al., 2003). This mechanism has been used to account for parafoveal-on-foveal effects stemming from unusual upcoming orthography (Rayner, Juhasz, et al., 2007; Starr & Inhoff, 2004).

One way to disentangle these two potential explanations is to include parafoveal primes that differ in the strength of their orthographic and visual relationship to the pre-boundary target word. This can be achieved with transposed and substituted-letters versions of the repeated parafoveal word: transposing letters within a prime (*ckae*) maintains a high level of orthographic similarity with the target word (*cake*) whereas substituting letters (*ctie*) reduces the orthographic similarity. Replacing the substituted letters with others of the same shape (e.g., descenders with descenders) ensures a basic visual similarity between the transposed and substituted primes. If a transposed letters (TL) prime reduces response times to a target word more than a substituted letters (SL) prime does, this is evidence that priming has occurred due to orthographic processing of the parafoveal word. This result would be inconsistent with E-Z Reader in which orthographic processing is assigned to the L1 stage of lexical processing (Reichle et al., 2007) that cannot take place for more than one word at a time. A TL/SL parafoveal-on-foveal priming comparison thus provides an opportunity for assessment of the E-Z Reader prediction that orthographic processing is confined to one word at a time.

Transposed-letters priming

This TL/SL prime comparison has also featured in the isolated word literature in a different capacity. In this context its importance has been in showing how orthographic similarity between a prime and target produces a priming effect, as TL primes (which alter only letter order) typically induce faster responses to the target than do SL primes (which alter letter identity). This is a huge literature, so only a few articles will be presented, with the intention of making the point that TL priming indicates the importance of letter identity over letter order.

The effect of orthographic priming was first demonstrated by Evett and Humphreys (1981) who found graphemic overlap increased the accuracy of target identification regardless of the letter case or lexical status of the prime stimuli, an effect known as form-priming; this effect was also observed in decreased lexical decision times (Forster & Davis, 1984). Forster et al. (1987) made the relevant comparison of nonword TL primes with nonword SL primes and found slightly smaller priming effects from the SL primes, although both conditions produced less priming than an identical prime condition. A potential reason for the reduced priming from stimuli with substituted letters was proposed by Peressotti and Grainger (1999) who claimed that, under an Interactive-Activation framework, there is target inhibition produced by substituted letters in a prime that masks any target facilitation from shared letters; the more differences between the features of the substituted letters and the features of the target letters, the greater the feature-letter inhibition generated. This would explain the facilitation provided by relative-position primes that contain no unrelated letters (e.g., Humphreys et al., 1990).

Perea and Lupker (2003) were amongst the first researchers to realise the wider theoretical utility of this comparison in determining the relative importance of letter identity over letter order during the input stage of word recognition. They employed a semantic priming paradigm in which the prime was semantically related to the target word (*judge* as the prime for *court*), or a nonword created by transposing (*jugde*) or substituting (*judpe*) the letters of the related prime. As might be expected, the priming levels from the TL nonwords were almost as high as those from the related word prime, and significantly higher than those from the SL nonword prime. The semantic level priming produced strongly implies that the TL primes were activating the lexical entry for the target word, rather than just its sublexical units. Interestingly, this TL effect was not replicated for primes formed by transposing the last two letters of the related prime (*judeg*).

The crucial next step taken by Perea and Lupker was to assess the ability of several models of isolated word recognition to account for these findings. They realised that this would be extremely difficult for any model relying on position-specific coding, such as the IAM (McClelland & Rumelhart, 1981), the activation-verification model (Paap et al., 1982), the multiple read-out model (Grainger & Jacobs, 1996) and the dual-route cascaded model (Coltheart et al., 2001) as these assume conjoint processing of letter order and identity. TL priming would only be predicted by models taking a more innovative approach to letter coding, including SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003), the overlap model (Gómez et al., submitted), the split-fovea model (Shillcock & Monaghan, 2001) and SOLAR (Davis & Bowers, 2006). Perea and Lupker focused on the spatial coding system implemented by SOLAR that employs an orthographic match calculator whose predicted TL priming effects match those seen in the data, but all of these recent models can account for TL priming thanks to their emphasis on letter identity and relative, rather than absolute, letter position.

What are the limitations on TL priming effects? As mentioned above, Perea and Lupker found that transpositions involving the last two letters of a prime reduced the facilitation from a TL prime to that of an SL prime; the authors speculated that the quality of letter position information might be higher for exterior letters. Similar work comparing exterior and interior letter transpositions has yielded mixed results (Grainger et al., 2006; Guerrera & Forster, 2008; Whitney & Cornelissen, 2008), with some modellers choosing to emphasise the role of exterior letters (Whitney, 2001) and others assigning equal weighting to all letters (Davis & Bowers, 2006; Gómez et al., submitted; Grainger & van Heuven, 2003). These models also differ in their ability to explain non-adjacent transposition priming, for example *caniso* is a more effective prime for *casino* than *caviro* (Perea & Lupker, 2004). Perea and Lupker (2004) believed that this effect was limited to transposed consonants only, as *cisano* was less effective than *caniso*, but this work was carried out in Spanish, a language whose words follow a very regular CVC structure. Repetition of this work in English by Lupker et al. (2008) led to the conclusion that any differences between consonant and vowel transposition are due to the higher letter frequencies of vowels, rather than any specific processing differences associated with the two letter groups. This work illustrates the care that must be taken to acknowledge the potential specific effects caused by the language in which an experiment is presented. Guerrera and Forster (2008) set a further challenge for these models with their finding of TL priming even when only two letters in an eight-letter prime were correctly positioned.

TL priming during reading

An important recent extension of the research concerning TL priming comes following the realisation by Johnson et al. (2007) that if an isolated word effect provides evidence against one class of models of word recognition, then if that effect is replicated during reading it strongly suggests those models are unsuitable as a template for word recognition in text reading. The question of how to characterise word recognition mechanisms is of interest to researchers modelling eye movement control during text reading who often remain vague with regard to the processing details (Radach & Kennedy, 2004). A few recent studies have attempted to address this problem with direct qualitative and quantitative comparisons of orthographic, phonological and lexical effects across isolated word tasks and reading; most studies have concluded that effects are similar in both domains (Folk & Morris, 1995; Jordan, Thomas, Patching, & Scott-Brown, 2003; Juhasz et al., 2003; Perea & Pollatsek, 1998; Pollatsek et al., 1992; Schilling et al., 1998) although some have recorded differences associated with the differing nature of the tasks (Inhoff et al., 1996; 2003). This work has the virtue of uniting two fields that have historically exerted little mutual influence. Johnson et al. realised that answering the simple question of whether TL effects occur in a reading situation embodies the same virtue.

Johnson et al. employed a parafoveal preview paradigm in their experiment as this involves priming of the post-boundary target word from the preview prime present until the boundary change immediately prior to the target word. The reduction in fixation durations on the post-boundary word is an indicator of the priming received from the preview and thus an indicator of the level of perceived similarity between the preview prime and post-boundary target stimuli (analogous to the reduction in lexical decision times following a masked prime in a typical single word priming experiment e.g., Forster & Davis, 1984). As shown in Figure 28, they compared fixation durations on the post-boundary word when the preview was either an identical, TL or SL nonword prime, allowing for investigation of how letter information is processed in the parafovea. If letter identity is extracted independently of letter position then the TL and identical word preview conditions should produce identical levels of priming, and more than the SL condition. If letter identity cannot be separated from letter position then the TL and SL previews should produce identical levels of priming, and less than that from the identical word preview.

```
The boy was playing with his | toys          (identical)
                           * |
The boy was playing with his | tyos          (transposed-letters)
                           * |
The boy was playing with his | tges          (substituted-letters)
                           * |
The boy was playing with his | toys          (post-boundary)
                             |  *
```

FIG. 28: The parafoveal preview conditions employed by Johnson et al. (2007)

The results from this experiment replicated the finding from isolated word recognition studies (e.g., Perea & Lupker, 2003) that TL previews provided more effective priming than SL previews, indicated by shorter first-pass fixations on the target word following a TL preview. However, TL previews were less effective than identical word previews, showing that while letter identity can be processed independently of letter position, processing is optimal if both types of information are correct and complete. An interesting additional finding was that TL effects disappeared when the amended letters were more than five letters from the start of the preview word, an effect which indicates how the loss of acuity or attenuation of attention in the parafovea is a factor in text reading but not in isolated word processing. Despite parafoveal acuity or attentional restrictions it appears that the word-final letter plays a privileged role in word recognition, as a seven-letter SL preview with the substituted letters at positions five and six (with the final letter preserved) provided more priming than did TL and SL previews whose final letter was one of the amended pair. This suggests that the processing of the identity of a word-final letter cannot be separated from the processing of its position.

This type of experiment sheds light on the nature of the lexical access that is taking place during text reading and therefore on the viability of particular isolated word recognition models in this extended capacity. Its results lead to the conclusion that during parafoveal word processing letter identity can be processed independently of letter order, except for the final letter of a word which must be correctly positioned. The only exception to these findings stems from the inevitable limitations that reduce processing capabilities for distant letters. The finding of TL priming effects during reading supports previous work from the isolated word recognition literature (e.g., Perea & Lupker, 2003) that has largely led to the abandonment of slot-based coding as the letter input mechanism for models of word recognition due to its conjunctive coding of letter identity and absolute, length-dependent position. This work has led to the invention of a number of new emergent models specifically designed with more flexible systems of letter input coding, such as open bigrams (Overlap Open-Bigram model; Grainger et al., 2006; SERIOL; Whitney, 2001), split-field grouping (split-fovea model; Shillcock & Monaghan, 2001) and spatial coding (SOLAR; Davis & Bowers, 2006), all of which are candidate systems for use in models of eye movement control during text reading. The question for the current experiment is whether the same results will also be observed with a parafoveal-on-foveal paradigm involving simultaneous presentation of the target and prime.

The current experiment

This experiment involves a repetition of the Repeated Word Parafoveal-on-Foveal task presented in Chapter 4, with the addition of TL and SL post-boundary stimulus conditions. As this is a test of parafoveal-on-foveal effects rather than parafoveal preview, the target word is instead the pre-boundary word and the analysis will indicate the influence of the parafoveal stimulus condition on fixations on the target word. Figure 29 presents the three experimental conditions: Repeated (target word repeated at post-boundary position); Transposed (two internal adjacent letters of the target word are swapped around); and Substituted (two internal adjacent letters of the target word are replaced with other letters).

The store had a *coat* *coat* that week (Repeated)

*

The store had a *coat* *caot* that week (Transposed)

*

The store had a *coat* *ceit* that week (Substituted)

*

The store had a *coat* *sale* that week (post-boundary)

*

FIG. 29: The three parafoveal word conditions and the boundary change (target, parafoveal and post-boundary words in italics; dotted lines indicate the boundary position; asterisks indicate fixation position)

As this experiment is designed to test the orthographic properties of the TL and SL parafoveal stimuli, low-level visual similarity between the TL and SL conditions will be maintained by substituting ascender letters for ascender letters, descenders for descenders, vowels for vowels and consonants for consonants. In order to maximise the distinction between letter identity and order embodied in these two conditions the transpositions/substitutions will not involve the final letter of the stimuli, as the results of Johnson et al. (2007) indicated that the last letter of a word is necessarily processed within its position. As before, the parafoveal stimulus is presented until the eyes cross the invisible boundary, at which point the parafoveal stimulus is changed to the meaningful post-boundary word.

Predictions

The isolated word experiments described above (e.g., Perea & Lupker, 2003; 2004) and in particular the parafoveal preview experiment carried out by Johnson et al. (2007) clearly lead to a prediction of shorter first-pass fixation durations (first fixation and gaze durations) in the Repeated parafoveal word condition than in the Substituted word condition. However, it is the comparison between the Transposed and Substituted conditions that is of most interest. If parafoveal letter identity cannot be separated from letter order then there should be no difference in the priming of the pre-boundary target obtained in these two conditions, as indexed by no difference in the first-pass fixation durations on the target word. This prediction stems from the tradition of slot-based coding employed as the input mechanism for models of isolated word recognition (e.g., IAM; McClelland & Rumelhart, 1981). However, if parafoveal letter identity is processed separately from letter order then this leads to a prediction of increased priming from the Transposed stimuli compared to the Substituted stimuli, a finding that would support a relaxed form of letter input coding in the word recognition mechanism of models of eye movement control during text reading. Given the clear rejection of slot-based coding by the current word recognition community (e.g., Davis & Bowers, 2006; Grainger, 2008; Whitney, 2001) and the identical levels of priming from both related letters conditions in the Orthographic FLLD task (regardless of letter order) the stronger prediction must be the latter.

The hypothesis of more priming in the Transposed condition is also predicted by those who advocate parallel lexical processing during text reading (e.g., Engbert et al., 2002; Inhoff, Starr, et al., 2003). The difference between the Transposed and Substituted conditions is only in their level of orthographic similarity to the pre-boundary word: they are equated on length, word shape and non-lexical status. It is only the similarity of their internal letters to the target word that varies, and thus if a Transposed-letters parafoveal prime leads to reduced viewing durations for the target word this is a strong orthographic parafoveal-on-foveal effect. This finding would not be predicted under a serial lexical processing framework such as E-Z Reader (Reichle et al., 1998) as this confines orthographic processing to one word at a time.

Although a parafoveal preview analysis will be carried out, there are no strong predictions for this. None of the three parafoveal word conditions provide a preview related to the post-boundary word, so any parafoveal preview findings are likely to be small. The only likely potential effect is that the Repeated condition provides a lexical preview and thus might cause less disruption in the eye movement pattern than the non-word previews of the Transposed and Substituted conditions. Fixation probability was included as a dependent variable but the number of regressions back to the pre-boundary area was not as only first-pass measures were of interest.

Method

Participants

30 students from the University of Edinburgh took part in this experiment in exchange for £10. They were all native English speakers with no language disorders and normal or corrected-to-normal vision, and none had participated in the previous eye-tracking experiments.

Design

In a similar manner to the Repeated Word n+1 experiment the independent variable was the properties of word n+1 prior to an invisible boundary change, and again there were three conditions: Repeated (repetition of word n), Transposed (repetition of word n with transposed internal letters) and Substituted (repetition of word n with substituted internal letters). The 69 experimental sentences were counterbalanced across the conditions with 10 participants assigned to each version of the experiment.

Materials

There were again 69 experimental sentences with 50 filler and 5 practice sentences. These were based on the materials used in the Repeated Word n+1 experiment. However, as one of the conditions in this experiment required the transposition of two internal letters those sentences containing target words whose internal letters were identical (e.g., *cook*, *wood*) were replaced with either sentences from the Repeated Word n-1 experiment or new sentences. New filler and comprehension questions were created in line with these changes.

This experiment again employed an invisible boundary located one pixel to the right of the target word, with the parafoveal word presented to the right of the boundary until the eye crossed the boundary and it was replaced by the post-boundary word. The Repeated condition was identical to the Repeated condition in the Repeated Word n+1 experiment, with the parafoveal word a repetition of the target word. The Transposed and Substituted parafoveal words were created from the target word. For the Transposed condition two of the internal letters were swapped around to create a non-word: these were the only internal letters in the four-letter target words and the 2nd and 3rd letters in the five-letter target words. For the Substituted condition two internal letters were substituted with letters that were different but maintained the same word shape and letter type as in the Transposed condition. Letters with ascenders were swapped for letters with ascenders (b, d, f, h, k, l, t), descenders for descenders (g, j, p, q, y), vowels for vowels and consonants for consonants. This did not mean that the word shape for the Repeated condition was the same as that for the Transposed and Substituted conditions (following Johnson et al., 2007). For example, if the Repeated parafoveal word was *cheap* then the Transposed parafoveal word was *cehap* and the Substituted parafoveal word was *culap*.

Apparatus

This was identical to the apparatus used in the Repeated Word n+1 eye-tracking experiment.

Procedure

The procedure was identical to that involved in the Repeated Word n+1 eye-tracking experiment.

Data selection

The data selection procedure employed was similar to that of the Repeated Word n+1 experiment. In this experiment there were boundary changes in all three conditions i.e., 69 sentences, so the maximum number of sentences in which participants could see a boundary change without their data being discarded was increased to 7 (10%). 16 participants' data were discarded under this rule. This is approximately three times the number of participants excluded in the Word n+1 experiment and this high number is probably due to the use of non-words as parafoveal stimuli which are more visually distinctive than words (even those that are semantically anomalous). This was likely to increase the visibility of the boundary change between the non-words and post-boundary words. This is in line with the work by Starr and Inhoff (2004) showing that the presence of an orthographically illegal non-word at position n+1 altered the fixation pattern on word n. One participant's data were excluded due to excessive errors in answering the comprehension questions and one participant's data were excluded as they only pressed the 'yes' button when answering questions so their comprehension level could not be determined.

Trials were discarded if the participant reported noticing the change for that trial, if the boundary was triggered by a blink or if the boundary change occurred during a fixation (typically on the boundary itself) for all three conditions: 20% of trials were discarded in this manner. A word was considered fixated if the eye landed on one of its letters or the space preceding it (Starr & Inhoff, 2004). Fixations less than 50 msecs or greater than 2000 msecs were considered outliers; 4 first fixations were removed due to their very short durations. This involved removing the fixation from the first fixation duration analysis and subtracting the fixation time from the gaze duration, but as all of these very short fixations were followed by re-fixations within the first-pass reading a positive fixation probability was recorded. First-pass measures excluded words that were skipped on first-pass, or fixations prior to or after regressions (Kliegl et al., 2006). This ensured that the only fixations retained for analysis were in a forward direction. First fixation durations, gaze durations and fixation probabilities were calculated; similar to the Word n+1 experiment, only first-pass measures were of interest.

Results

Parafoveal preview analysis

In a similar manner to the Word n+1 experiment the initial analyses were carried out on the effect of the different parafoveal word conditions on the responses to the post-boundary word itself i.e., a parafoveal preview analysis. As Table 12 and Figure 30 show, first fixation durations on the post-boundary word were slightly shorter in the Transposed condition than the other two conditions.

Table 12

Mean first fixation durations (and standard deviations) in milliseconds as a function of parafoveal preview condition

Parafoveal preview condition		
Repeated	Substituted	Transposed
264.2 (49.7)	267.8 (52.0)	256.5 (44.4)

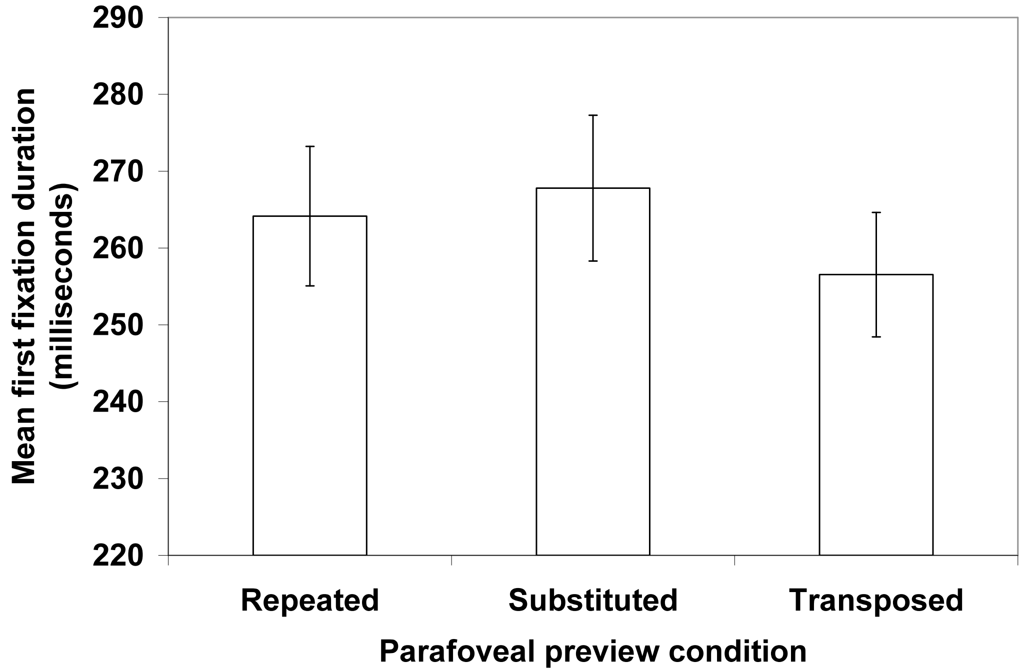

FIG. 30. The effect of parafoveal preview condition on mean first fixation durations; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA did not support this difference [$F_1(2,58) = 1.90$, *ns*: $F_2(2,136) = 0.53$, *ns*] and neither did a corresponding LME analysis [$F(2,1161.76) = 1.09$, *ns*].

As Table 13 and Figure 31 show, the gaze duration data followed a similar pattern, with a slight trend towards shorter fixations in the Transposed condition again not supported by a one-way repeated-measures ANOVA [$F_1(2,58) = 3.16$, *ns*; $F_2(2,136) = 1.05$, *ns*] or an LME analysis [$F(2,1164.22) = 0.82$, *ns*].

Table 13

Mean gaze durations (and standard deviations) in milliseconds as a function of parafoveal preview condition

Parafoveal preview condition		
Repeated	Substituted	Transposed
290.9 (60.4)	288.7 (59.2)	282.1 (51.4)

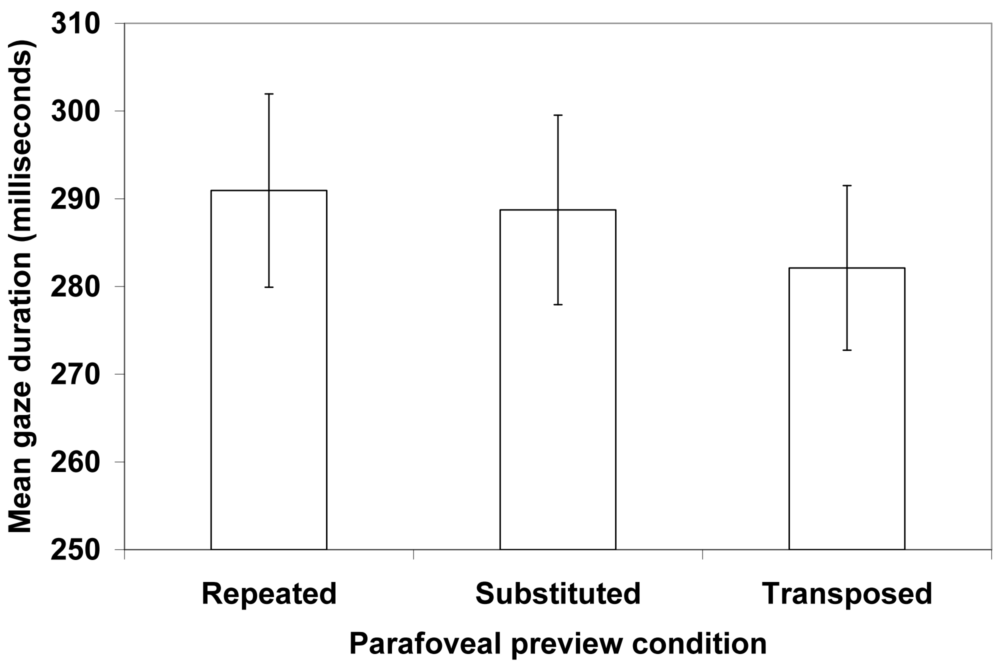

FIG. 31. The effect of parafoveal preview word condition on mean gaze durations; error bars indicate standard error of the mean

The results for fixation probability indicated a different trend, with a slightly higher probability of fixation in the Substituted condition.

Table 14

Mean fixation probabilities (and standard deviations) in milliseconds as a function of parafoveal preview condition

Parafoveal preview condition		
Repeated	Substituted	Transposed
0.69 (0.18)	0.72 (0.18)	0.68 (0.17)

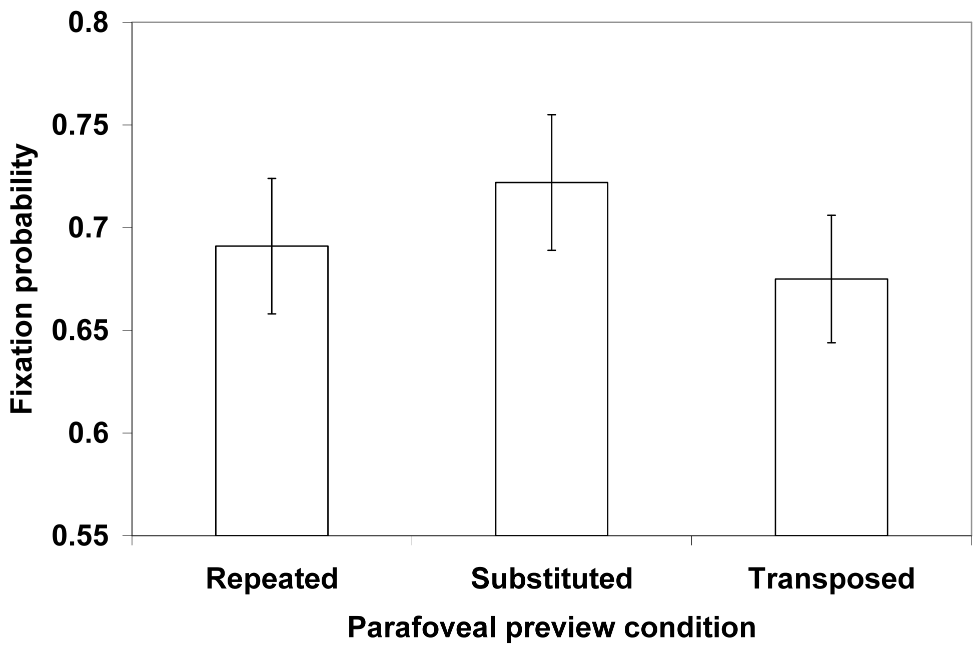

FIG. 32. The effect of parafoveal preview word condition on fixation probabilities; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA showed that there was a marginally significant main effect of parafoveal preview word condition by participants [$F_1(2,58) = 3.11$, $p = 0.083$] but not by items [$F_2(2,136) = 1.48$, *ns*]. Post-hoc paired-samples t-tests with a Bonferroni correction showed that post-boundary words in the Substituted condition were marginally more likely to be fixated than those in the Transposed condition [$t_1(29) = 2.3$, $p = 0.052$].

Parafoveal-on-foveal analysis

The focus of this experiment was on the effect of parafoveal word condition on fixations on the target word. Table 15 and Figure 33 show that the first fixation durations on the target word were very similar in the three parafoveal word conditions.

Table 15

Mean first fixation durations (and standard deviations) in milliseconds as a function of parafoveal word condition

Parafoveal word condition		
Repeated	Substituted	Transposed
214.2 (36.0)	216.0 (34.0)	212.7 (26.4)

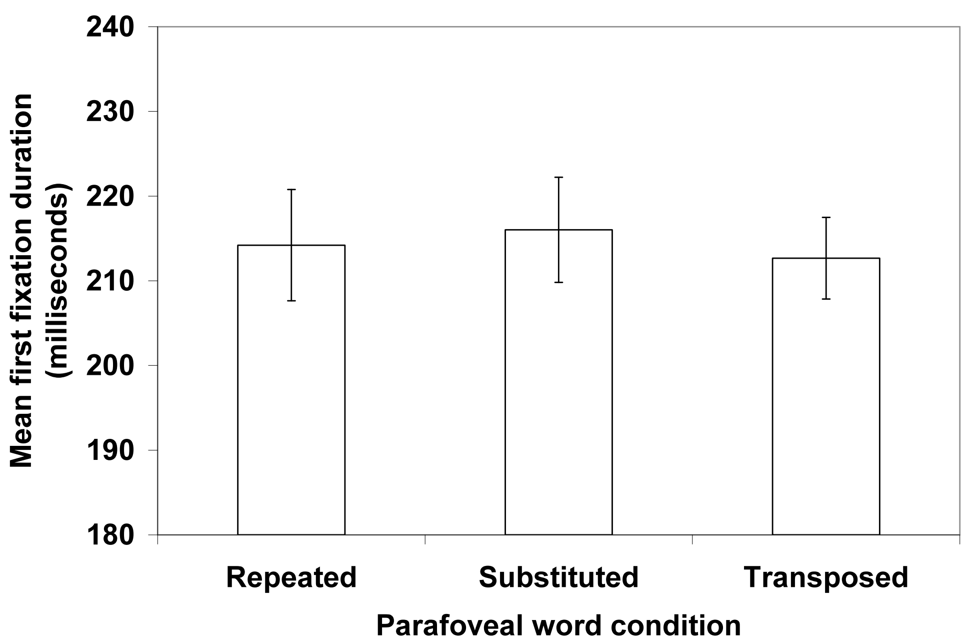

FIG. 33. The effect of parafoveal word condition on mean first fixation durations; error bars indicate standard error of the mean

This similarity is borne out in a one-way repeated-measures ANOVA which showed no significant difference between the conditions [$F_1(2,58) = 3.16$, *ns*; $F_2(2,136) = 0.31$, *ns*]. An LME analysis confirmed this finding [$F(2,1187.39) = 0.54$, *ns*].

The results for the gaze duration data were more interesting, with the mean duration for the Substituted condition being over 10 milliseconds longer than for either of the other two conditions.

Table 16

Mean gaze durations (and standard deviations) in milliseconds as a function of parafoveal word condition

Parafoveal word condition		
Repeated	Substituted	Transposed
223.5 (39.2)	237.3 (40.3)	226.3 (37.1)

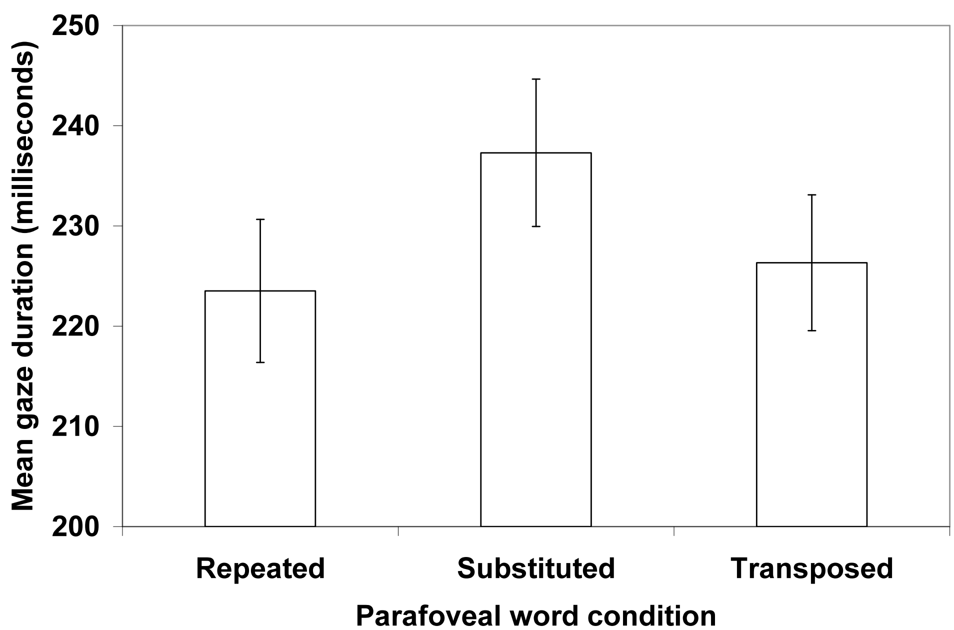

FIG. 34. The effect of parafoveal word condition on mean gaze durations; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA found that there was a marginally significant effect of post-boundary condition [$F_1(2,58) = 2.79$, $p = 0.069$; $F_2(2,136) = 3.01$, $p = 0.053$]. Post-hoc paired-samples t-tests with a Bonferroni correction showed that fixations in the Substituted condition were marginally longer than those in the Repeated condition by participants only [$t_1(29) = 2.45$, $p = 0.061$]. These marginal findings were supported by an LME analysis which found a significant main effect of post-boundary word condition [$F(2,1192.45) = 4.81$, $p < 0.01$]. Post-hoc paired-samples t-tests with a Bonferroni correction confirmed the difference between the Repeated and Substituted conditions [$t(1194.38) = 2.70$, $p < 0.05$] and showed that fixations in the Substituted condition were also significantly longer than those in the Transposed condition [$t(1188.30) = 2.66$, $p < 0.05$]. However, there was no significant difference between the Repeated and Transposed conditions [$t(1193.67) = 0.006$, *ns*].

Table 17 and Figure 35 show that the results for the fixation probability variable were very similar to those for first fixation duration.

Table 17

Mean fixation probabilities (and standard deviations) as a function of parafoveal word condition

Parafoveal word condition		
Repeated	Substituted	Transposed
0.68 (0.18)	0.68 (0.19)	0.65 (0.17)

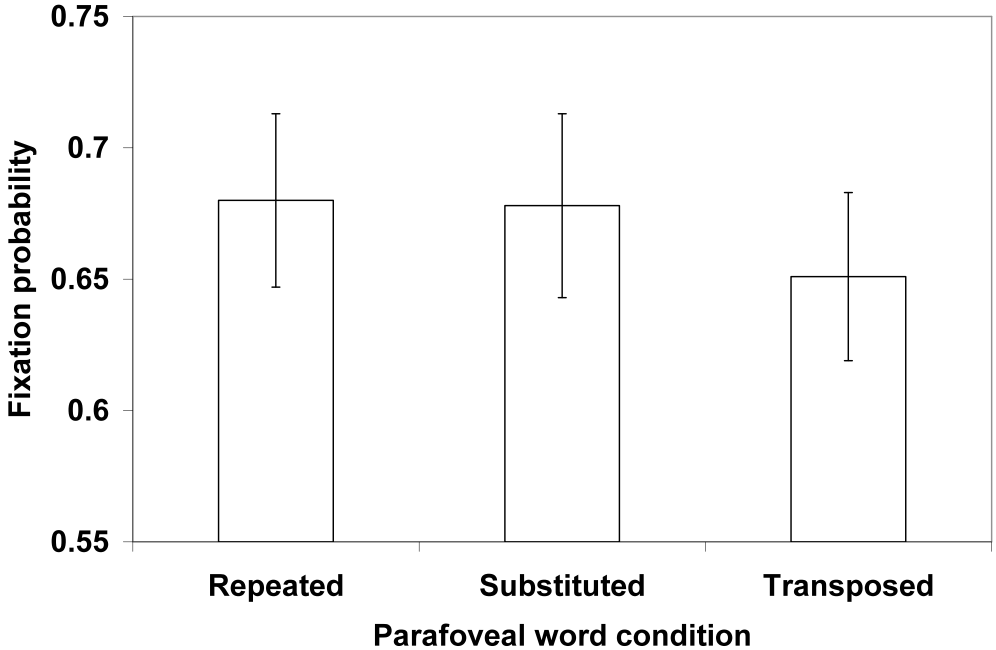

FIG. 35. The effect of parafoveal word condition on fixation probabilities; error bars indicate standard error of the mean

A one-way repeated-measures ANOVA found that there was no main effect of post-boundary word condition on fixation probabilities [$F_1(2,58) = 0.89$, *ns*; [$F_2(2,136) = 0.71$, *ns*].

Discussion

Parafoveal-on-foveal predictions

This experiment extended the parafoveal-on-foveal priming paradigm presented in the Repeated Word n+1 experiment by adding a comparison of the priming received when the post-boundary word was a transposed or substituted-letters version of the pre-boundary target word. This comparison tested the orthographic rather than visual processing of the post-boundary word and as such is an indicator of whether lexical processing of text proceeds in a serial or parallel fashion. It had the additional benefit of assessing the suitability of slot-based coding as the input mechanism for models of text reading, as if letter identity and order cannot be processed separately then there should be no more priming from the Transposed condition than the Substituted condition. In order to test these predictions participants read a series of sentences containing an invisible boundary followed by a repetition of the pre-boundary word or its transposed/substituted amendment while their eye movements were recorded using a head-mounted eye-tracking device.

The deliberate visual similarity of the three parafoveal word conditions meant that the difference in their effect on the first-pass fixation pattern on the target word n was slight. In fact, no difference between the first fixation duration or fixation probability measures was recorded. However, the gaze duration data indicated that fixations were significantly shorter in the Repeated and Transposed conditions than in the Substituted condition, with no difference between the Repeated and Transposed conditions. These reduced gaze durations suggest that priming from the parafoveal word has reduced the processing time required for the foveal target word. This effect supports the prediction from the isolated word recognition literature that a transposed-letters prime is more similar to its baseline word than a substituted-letters prime due to letter identity exerting a greater effect than letter order. It also supports the prediction that parallel orthographic processing of adjacent words is a feature of text reading. The fact that this finding attained significance in the gaze duration data but not the first fixation duration data indicates the subtlety of the influence from the parafoveal word that only became apparent following more than one fixation on the target word.

Parafoveal preview predictions

This experiment was not designed with an interesting parafoveal preview analysis in mind but it nevertheless revealed a minor effect worthy of further investigation. The analysis revealed that the probability of fixating the post-boundary word was marginally higher in the Substituted condition than in the Repeated or Transposed conditions. A tentative explanation for this could be that the Substituted parafoveal stimulus was more orthographically unusual than either the Repeated parafoveal word or the Transposed parafoveal stimulus that contained all of the letters of the Repeated word. This unusual orthography could have attracted attention to the post-boundary word and reduced word skipping. This goes beyond the concept that non-lexical orthography in parafoveal vision alters the eye movement pattern (e.g., Starr & Inhoff, 2004), as in both the Substituted and Transposed conditions the post-boundary items were non-words; the difference between them lay in whether they contained the same letters as a lexical word. This finding is again suggestive of orthographic-level processing prior to fixation on a word and emphasises the flexibility of letter position encoding in the parafovea. However, as noted above this result achieved only marginal significance and the work by Johnson et al. (2007) provides stronger evidence for this effect.

Implications for slot-based input coding

The gaze duration results for the target word revealed that the Repeated and Transposed parafoveal words provided identical levels of priming for the target word, and that both provided significantly more priming than did the Substituted condition. This implies that correct letter identity is more important than correct letter position in word recognition and provides support for recent models of word recognition (Davis & Bowers, 2006;

Grainger & van Heuven, 2003; Gómez et al., submitted; Shillcock & Monaghan, 2001; Whitney, 2001) that do not rely on the conjunctive coding of letter identity and order inherent in slot-based coding models (Coltheart et al., 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap et al., 1982). These recent models also find support from isolated word experiments whose transposed-letters priming effects mirror those of this experiment (Dare & Shillcock, 2005; Forster et al., 1987; Perea & Lupker, 2003; 2004; Peressotti & Grainger, 1990).

This finding of transposed-letters effects in reading is similar to the work by Johnson et al. (2007) in their parafoveal preview demonstration of decreased first-pass fixation durations on the post-boundary word when its preview was a TL prime compared to an SL prime. If isolated-word masked-priming experiments demonstrating TL effects have caused modellers to reject slot-based coding as an input mechanism for models of isolated word recognition, then the eye-tracking experiments of Johnson et al. and this chapter seem sufficient evidence to reject slot-based coding as a candidate input mechanism for lexical access during reading. These experiments fall into the small but increasing number starting the discussion of how the findings from single word and text reading studies can be integrated for the mutual benefit of both, hitherto largely separate, fields of research (Folk & Morris, 1995; Grainger et al., 2008; Inhoff et al., 1996; 2003; Jordan, Thomas, Patching, & Scott-Brown, 2003; Juhasz et al., 2003; Perea & Pollatsek, 1998; Pollatsek et al., 1992; Radach & Kennedy, 2004; Schilling et al., 1998). This dialogue will allow for increased specificity of lexical processing in models of eye movement control during text reading, as well as for increased awareness of the even less considered interaction of how text-level factors can influence models of isolated word recognition.

Implications for parallel processing

The second implication of the similarity between the Repeated and Transposed conditions and their increased priming compared to the Substituted condition is of parallel orthographic processing of the target and parafoveal stimuli. The only difference between the Transposed and Substituted primes was in their orthographic similarity to the target word, as the letter composition of the former was identical to that of the target whereas the letter composition of the latter differed from that of the target by two letters. Simultaneous orthographic processing of words n and n+1 is a parafoveal-on-foveal effect whose existence goes against the concept of serial lexical processing of text advanced in early versions of E-Z Reader (Reichle et al., 1998). Later versions of the model (Reichle et al., 2003) include a parallel pre-attentive visual processing stage that scans the gross features of upcoming words. This stage could account for parafoveal-on-foveal effects stemming from unusual orthography (Starr & Inhoff, 2004) but the identical word shape of the Transposed and Substituted conditions means that this processing cannot distinguish between them. Orthographic processing is required to account for this result, a processing level that is part of the L1 stage of lexical processing in E-Z Reader. This stage demands attention, a resource that according to Reichle and colleagues cannot be spread over more than one word at a time.

The term 'parafoveal-on-foveal' was coined to describe the effect of the properties of word n+1 on the processing of word n and it implies the parallel processing of these words. Such effects are easily explained by a model such as SWIFT (Engbert et al., 2002) in which lexical processing occurs in parallel across four words around the fixation, albeit with reduced processing for letters further from fixation according to a Gaussian processing distribution. Parallel lexical processing leads to a build-up of activation across these words, and the word with the highest level of activation is chosen as the saccade target. Under this framework, information is sought from a larger area than in a serial model, and this allows it to explain parafoveal-on-foveal effects of simultaneous lexical processing.

Future work

Having determined that parallel processing of text, at least at the orthographic level, seems likely, and having continued the fledgling discussion of how word recognition proceeds during reading, this now raises the question of whether the fact that we process words in conjunction with their neighbours affects our reactions to them when they are in isolation. Isolated word recognition paradigms suffer from the criticism of being 'unnatural' as we almost always encounter words in context and surrounded by other words. Chapter 7 moves on to discuss the topic of amending isolated word paradigms to add some 'context' using flanking letters to address the question of how much our continued exposure to text conditions our responses to words in isolation.

Chapter 7
The Context Flanking Letters Lexical Decision Task
Introduction

Aims of the chapter

A major focus of this thesis is on the interaction between isolated word processing and text reading, and so far it has discussed how standard effects found in isolated word experiments can also be demonstrated in text (e.g., Johnson et al., 2007) and thus how the conclusions that are drawn from the isolated word work can be incorporated into the lexical access mechanisms that are implemented in text reading models, at least in these cases. An alternative approach to the task of integrating these two topics is to investigate whether our responses to isolated words are influenced by the fact that the typical presentation of words is when they are surrounded by other words as part of a sentence. If the finding from the text processing literature was of words processed consecutively this would be a moot point, but even those who advocate serial lexical processing (e.g., Reichle et al., 1998) accept that there is simultaneous visual processing of more than one word, and there is increasing support for the position that lexical processing is also simultaneous (e.g., Kliegl, 2007; Vitu et al., 2004; see chapters 4 and 6). This chapter therefore presents a version of the Flanking Letters Lexical Decision (FLLD) task to determine whether an appropriate letter context surrounding an isolated word reduces processing time for that word.

Transitional probability

Research into the effect of the presence of text on word processing is not new. McDonald and Shillcock (2001) noted that models of isolated word recognition designed to account for lexical variability rely on the standard variables of frequency, ambiguity etc. that differentiate words without reference to their environment. They described a new variable: Contextual Distinctiveness (CD), a measure of the lexical environment of a word, determined by calculating the distribution of words with which it co-occurs in a corpus. They use the phrase *run amok* to illustrate this new variable: the word *run* can co-occur with many other words and so its contextual distinctiveness is low compared with *amok* whose presence strongly constrains the identity of the words around it and so is high on the contextual distinctiveness scale. In support of the psychological utility of this variable is their finding that words with larger CD scores tended to require longer lexical decision times than did words with low CD scores. Although CD and word frequency are highly correlated, it appeared that CD was the better predictor as when the effects of CD were partialled out the correlation between frequency and lexical decision reaction times was no longer significant.

McDonald and Shillcock (2003a, 2003b) extended this work from a variable measuring the aggregate informativeness of the context of single words to a measure of the likelihood of co-occurrence of two specific words, the transitional probability of co-occurrence. They suggested that readers' implicit knowledge of this statistic could serve as an aid to lexical processing. This is a measure of the predictability of a word, a variable that is typically computed using the subjective judgement of readers as to which word best completes a given phrase (Cloze task). The proportion of responses corresponding to each word given is calculated as the contextual predictability of that word given that preceding phrase, a measure that is clearly dependent on readers' subjective semantic knowledge. High contextual predictability typically serves to reduce fixation durations and increase probability of skipping for a predictable word (e.g., Balota et al., 1995; Rayner & Well, 1996). The transitional probability of two words is instead an objective measure of predictability that does not require 'high-level' knowledge of word meanings, and includes both the forwards probability of word n given word n-1 (*away* given *throw*), and the backwards probability of word n given word n+1 (*throw* given *away*).

The authors carried out two experiments assessing the importance of transitional probability over and above that of contextual predictability. A corpus of eye movements recorded during text reading (McDonald & Shillcock, 2003b) revealed that both forwards and backwards transitional probabilities acted as unique predictors of first fixation and gaze durations, with fixation durations increasing when transitional probability decreased. The potential role for forwards transitional probability as an independent lexical variable was supported by the findings from an experiment (McDonald & Shillcock, 2003a) in which participants read sentences containing word pairs whose transitional probabilities were either high or low. For example, the word pair *avoid confusion* has a high transitional probability compared to the similar word pair *avoid discovery*. The similar low contextual predictability of these word pairs was independently verified by participants in a cloze task and mean predictability comparison. They reported an 11 millisecond increase in first fixation durations on the second word when the transitional probability was low.

These results led the authors to suggest that the statistical regularities such as transitional probability that are inherent in written language are a useful source of information for efficient anticipation of upcoming words. Distributional learning of word co-occurrence statistics might have a role to play in word reading independent of contextual predictability information. This provides indirect support for the notion of parallel processing of text that is the focus of this thesis. More direct evidence comes from the backwards transitional probability results (McDonald & Shillcock, 2003b) indicating that when the probability of word n given word n+1 was high (*wreak* given *havoc*), first fixation and gaze durations on word n were reduced. This is a parafoveal-on-foveal effect of the knowledge of word n+1 affecting the response to word n. Transitional probability is a lexical variable such as word frequency or imageability, but one which places the word firmly in the context of its neighbouring words, and so could provide an important link between the fields of isolated word recognition and text reading.

However, Frisson, Rayner, and Pickering (2005) argued that the experimental sentences employed by McDonald and Shillcock (2003a) were not sufficiently constrained in their contextual predictability. Although small, the Cloze values for the high transitional probability target word pairs were higher than those for the low probability pairs, so a difference in contextual predictability could have confounded their findings. Replication of this work by Frisson et al. (2005) using materials whose cloze probabilities were more closely matched across the high and low transitional probability conditions led to the disappearance of the independent effect of transitional probability; they also founnd no evidence for the influence of backwards probability. They argued that it is unlikely that transitional probability effects occur independently of contextual predictability effects.

The current experiment

There is clearly some controversy over the utility of transitional probability for readers as a means of increasing reading efficiency. One way to investigate this topic is to try to separate contextual predictability and transitional probability; in other words, to remove the 'high-level' contextual information while retaining the 'low-level' probability statistic. This can be achieved using a variation of the FLLD task with flanking letters that provide a letter 'context' around the target word. The FLLD task retains the advantages of a tightly controlled lexical decision task with a clear outcome while also acting as a 'snapshot' of text. If the processing of a fixated word is tightly coupled to the processing of the letters surrounding that word, these letters could condition our responses to that word even in an isolated word processing paradigm; this would be a strong test of whether the information available from multiple words is processed in parallel.

The strongest comparison would be of the bigrams that are the most and least likely to co-exist with the word under consideration for lexical decision i.e., bigrams that had the highest or lowest transitional probability with that word. However, extraction of these most and least likely word-bigram pairs from a corpus (the British National Corpus, or BNC) revealed that the most likely bigrams adjacent to almost every word were *he* or *th*, indicating that the previous or next word respectively was *the*. Other very common bigrams were short function words such as *or*, *an* or *it*. The least frequent were orthographically illegal letter combinations such as *qq* or *zx* that were almost certainly due to a misspelling. This method would lead to a comparison of words flanked by bigrams that came from a very restricted group (high likelihood condition) or that stood out due to their peculiar letter combinations (low likelihood condition).

Therefore, the bigrams chosen were instead those whose frequency in one position was most different from their frequency in the other position. For example, *qu* is much more frequent as the start of a word than the end of a word (*quick*, *quiet*), whereas *lt* is much more frequent at the end of a word than at the start (*hilt*, *spilt*). The bigrams in their more frequent position formed a letter context around the central word that would be plausible in a text context, whereas when the bigrams were in their less frequent position it would be implausible that this would occur as part of a text. This formed two conditions: Implausible and Plausible, and Figure 36 illustrates the Plausible and Implausible conditions.

lt rock qu *(Plausible)*

qu rock lt *(Implausible)*

FIG. 36: The two flanking letters conditions in the Context Flanking Letters Lexical Decision task

One potential criticism of this method of bigram choice is that it is not a specific test of the effects of transitional probability, as neither the most absolutely frequent bigrams, nor those that occurred most frequently with each stimulus word, were necessarily used. There were two reasons for this. One reason, mentioned above, was that there was a very small group of high frequency bigrams that were either lexical items or indicators of *the* which is the most frequently occurring word in English; similarly, there was a small group of the most infrequent bigrams that were made redundant by their orthographic illegality. The other was that this relative frequency method meant that the bigrams included in the two conditions differed only by their positions within the stimulus array, allowing for a fair and direct comparison. Despite the absence of the very specific measure of transitional probability this setup should allow for a valid and informative assessment of the plausibility of letter context on lexical decision reactions in the absence of confounding semantic predictability information.

Predictions

The prediction for this experiment is simple: if the probability of the co-occurrence of a word with those that surround it is routinely calculated and acts as an independent lexical variable, then it is possible that the effects of more and less plausible letter contexts should be evident in the responses to words outwith a text presentation. More specifically, lexical decision times to a word should decrease when that word is flanked by bigrams that create a plausible letter context (Plausible condition) compared with when they create an implausible letter condition (Implausible condition). However, if transitional probability is not independent of contextual predictability then when the semantic information about upcoming and previous words is removed, letter-level context effects should exert no influence on lexical decision reaction times.

Method

Participants

16 University of Edinburgh students were tested and received £2.50 for their time. There were 4 men and 12 women, all of whom were native English speakers with no language disorders and normal or corrected-to-normal vision. They had an average age of 23 years (*SD* = 4). Eleven were right-eye dominant and 5 left-eye dominant, and they all self-reported as right-handed on the Edinburgh Handedness Inventory (Oldfield, 1971) with a mean score of 6.5 and a range of 3.5-8.5. None of the participants had taken part in the previous FLLD experiments.

Materials

The Flanking Letters Lexical Decision paradigm was employed, with central 4-letter strings flanked by bigrams, but this time the bigrams created either a plausible or implausible letter context. One hundred and forty-four 4-letter words (72 high and 72 low frequency) and 144 4-letter nonword fillers were used. The words and nonwords used were those from the Timed FLLD experiment.

The rationale behind the Plausible and Implausible conditions was to create a letter context that most or least resembled a potential letter context that could occur around a word in text. A version of the BNC corpus was used to provide the frequency data for all of the bigrams (aa-zz) that occurred at the start and ends of words. The difference in frequency of occurrence as the start and end of words was calculated for each bigram, and the bigrams with the greatest relative difference between these positions were chosen. When the bigrams were presented in their more frequent position they formed part of the Plausible condition, and when they were presented in their less frequent position they formed part of the Implausible condition. Words were only paired with bigrams that contained none of the same letters as the word, and the bigrams on either side of the word in one condition were not necessarily yoked together in another condition. All of the stimuli were presented in bold lowercase 14-point Courier New font.

Design

This experiment involved two variables, central word frequency (high and low) and the plausibility of the flanking bigrams as a context in text (plausible and implausible), making a 2x2 within-subjects design. These variables were combined to make 4 conditions: high plausible, high implausible, low plausible, and low implausible, and in order for each participant to only encounter each item once each item was assigned to only one of the four conditions per experiment in a counterbalanced Latin Square design. In a similar manner to that employed in the Timed FLLD experiment the order of the two halves of the experiment and the finger (middle/index) used to indicate the word-nonword decision were also counterbalanced and included in the design to make a total of 16 versions of the experiment.

Procedure

The procedure for this experiment was almost identical to that used in the Timed FLLD experiment. The only difference was that the stimuli were presented on the computer screen until the lexical decision was made, rather than the stimuli being presented for only 150msec and then removed. This was to allow the presentation to more closely mimic the experience of text reading in which a word is fixated until there is an information-processing reason for the eyes to move, most typically when the recognition of the word is achieved allowing the integration of the word into the understanding of the text.

Data selection

This was identical to that carried out for the Timed FLLD experiment, except that the accuracy scores were out of 36 for participants and out of 8 for items.

Results

Reaction times

As Table 18 and Figure 37 show, high frequency words were responded to approximately 90 msecs more quickly than low frequency words, but context plausibility appeared to have little effect.

TABLE 18

Mean reaction times (and standard deviations) as a function of word frequency and bigram context plausibility.

	Bigram context	
	Plausible	Implausible
Reaction time (milliseconds)		
High frequency words	644.5 (79.8)	650.3 (82.4)
Low frequency words	759.0 (100.2)	743.3 (90.7)

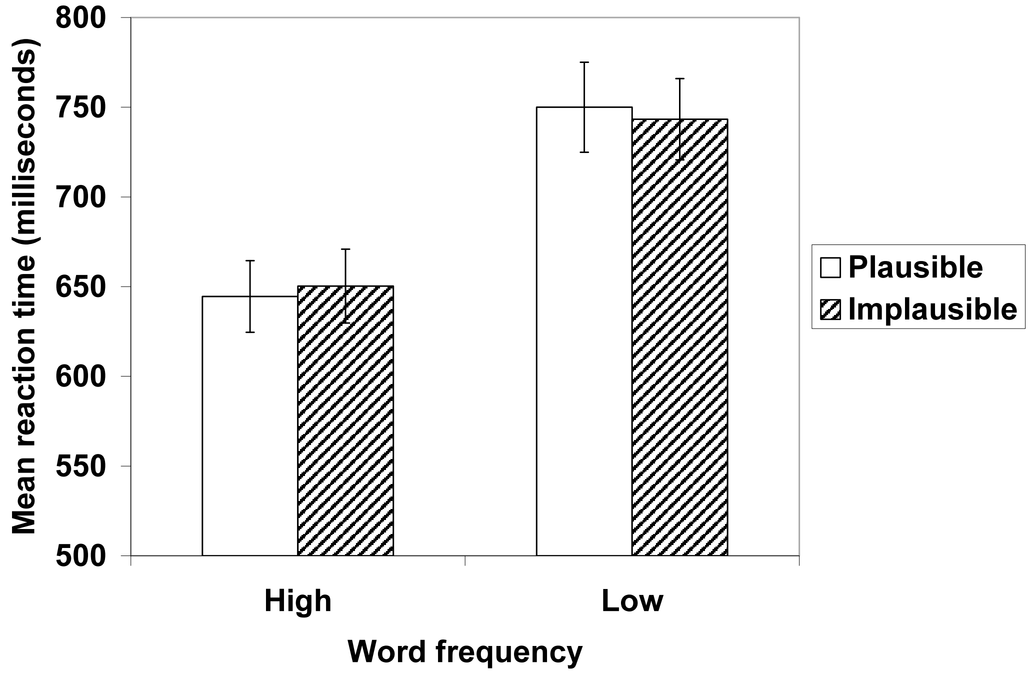

FIG. 37. The effect of frequency and bigram context plausibility on lexical decision reaction times; error bars indicate standard error of the mean.

A two-way repeated-measures ANOVA (by items this was a mixed ANOVA as word frequency is between-subjects) showed that although there was a main effect of word frequency [$F_1(1,15) = 135.288$, $p < 0.001$; $F_2(1,142) = 84.866$, $p < 0.001$], there was no main effect of bigram context on reaction times [$F_1(1,15) = 0.005$, *ns*; $F_2(1,142) = 2.539$, *ns*]. By subjects, there was no significant interaction [$F_1(1,15) = 0.872$, *ns*], so no items analysis was carried out. An LME analysis confirmed the main effect of frequency [$F(1,131.13) = 105.19$, $p < 0.001$] and lack of effect of bigram context [$F(1,1934.40) = 0.01$, *ns*], and did not produce a significant interaction between the two [$F(1,1934.49) = 0.93$, *ns*].

Accuracy scores

As Table 19 and Figure 38 show, accuracy appears to decrease for low frequency words but bigram context again appears to have little effect.

TABLE 19

Mean accuracy scores (and standard deviations) as a function of word frequency and bigram context.

	Bigram context	
	Plausible	Implausible
Accuracy (out of 36)		
High frequency words	35.1 (1.3)	34.4 (1.6)
Low frequency words	30.8 (3.4)	30.4 (2.4)

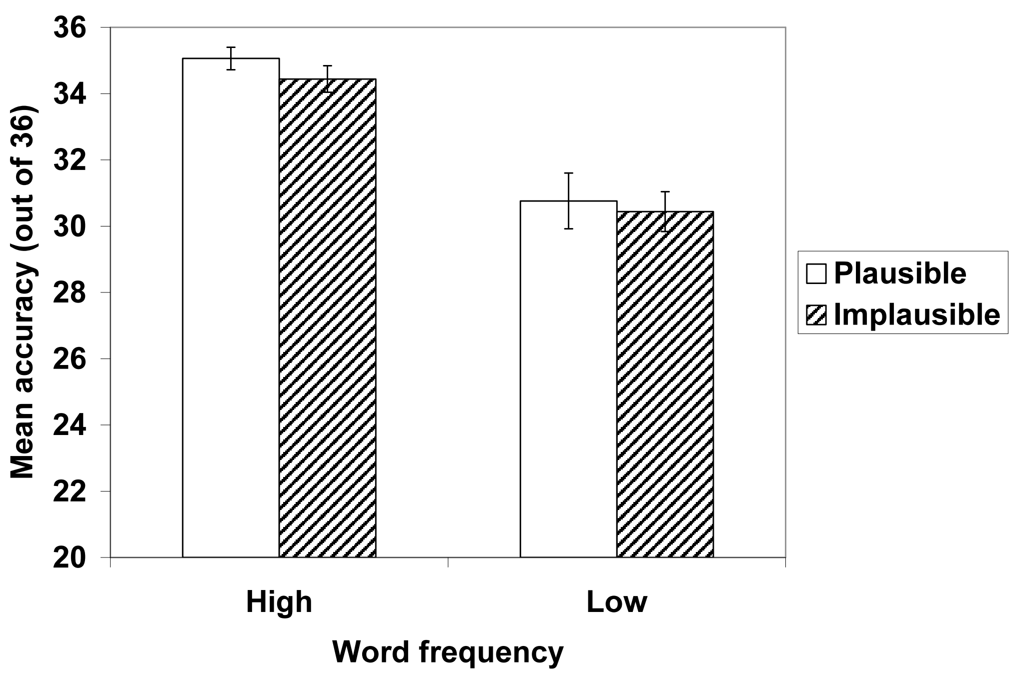

FIG. 38. The effect of frequency and bigram context on accuracy scores; error bars indicate standard error of the mean.

A 2-way repeated-measures ANOVA showed that again although there was a main effect of word frequency [$F_1(1,15) = 34.162$, $p < 0.001$; $F_2(1,142) = 38.151$, $p < 0.001$], there was no main effect of plausibility [$F_1(1,15) = 1.455$, *ns*; $F_2(1,142) = 0.277$, *ns*] and there was no interaction [$F_1(1,15) = 0.142$, *ns*; $F_2(1,142) = 0.141$, *ns*]. This does not provide support for the hypothesis that bigram context plausibility affects lexical decision accuracy.

Discussion

Letter context predictions

This experiment was designed to investigate the impact of our continual encounter with words in context on our responses to words presented in isolation. One potential variable that spans the gap between the fields of isolated word recognition and text reading is the transitional probability of the co-occurrence of two words, a statistical lexical variable distinct from knowledge-based contextual predictability effects. McDonald and Shillcock (2003a, 2003b) demonstrated the independent contribution of this variable in both experimental and corpus-based work, showing that when the transitional probability between two words was high fixation durations on the first word were reduced. This suggests distributional learning of word co-occurrence information, and implies parallel processing of text is common. However, Frisson et al. (2005) found no evidence for the existence of this variable when contextual predictability was more tightly controlled.

In this experiment participants executed lexical decisions to stimuli flanked by bigrams of letters (the FLLD task) but with the bigrams forming more or less plausible letter contexts around the central word. The bigrams chosen were those that had the greatest difference in frequency of occurrence as the initial and final letters of all of the words in a corpus; when arranged in their more frequent position this formed the Plausible condition and when in their less frequent position this formed the Implausible condition. This word+bigrams display acted as a ‘snapshot’ of text, with the advantage of a simple and well-defined isolated word response.

The results of the lexical decision task did not support the hypothesis that our responses to isolated words are conditioned by our exposure to text. Although word frequency had the standard effect of decreasing lexical decision response durations and increasing response accuracy (e.g., Forster & Chambers, 1973), letter context plausibility had no significant impact on either measure. The results of the two-way ANOVA of frequency and plausibility on the reaction time measure indicated an interaction between the two variables, but this was not confirmed in a follow-up LME analysis. This result is in the spirit of the work by Frisson et al. (2005), who found no evidence of a role for word co-occurrence information as distinct from semantic contextual predictability.

Implications and future work

This experiment found no evidence that contextual effects occur outside of text presentations. It is well-established that some of the factors that affect lexical access during text reading also impact our responses to isolated words, such as frequency (Schilling et al., 1998) and orthographic neighbourhood size (Perea & Pollatsek, 1998) but it appears that a more complete representation of text than was presented here is required for contextual effects to become apparent. Although the flanking letters in this experiment formed a plausible or implausible letter context, they were not lexical items and contained no 'higher-order' information other than their probability of occurrence. Although this experiment did not explicitly test transitional probability, this result suggests that transitional probability, the statistic of simple word co-occurrence independent of word-level semantic knowledge, is likely to play little part, if any, in aiding lexical access during reading. In contrast, contextual predictability is a well-established predictor of ease of lexical processing (e.g., Balota et al., 1985).

This thesis has thus far established the likelihood of parallel orthographic processing during both isolated word and text processing. It seems that this does not extend to orthographic letter-word co-occurrence statistics acting as lexical variables in the manner of frequency and orthographic neighbourhood. However, as noted in the Introduction this experiment was not a true test of transitional probability but rather an approximation of more and less likely context effects, and the transitional probabilities of the word stimuli and their flanking bigrams were not calculated. The possibility remains that a comparison of words flanked by bigrams with a high versus low transitional probability would yield a significant result. This was not implemented in this experiment due to the predominance of lexical items (e.g., *an*, *or*) as the bigram with the highest probability of co-occurrence with the four-letter words analysed. An alternative approach would be to instead utilise those words that form part of a phrase such as *wreak havoc* or *rolling stone* in which the second word is highly likely given the first. Figure 39 illustrates the High Probability and Low Probability conditions in this proposed follow-up experiment, with the Low Probability condition formed from the High Probability condition of another phrase (provided that the calculation of this transitional probability was sufficiently low).

wreak ha	*(High Prob)*
wreak st	*(Low Prob)*
rolling st	*(High Prob)*
rolling ha	*(Low Prob)*

FIG. 39: The formation of the High and Low Transitional Probability conditions in a potential follow-up experiment

Although the control of the properties of the lexical stimuli themselves would become more difficult, this arrangement would provide a stronger test of transitional probability (as distinct from contextual predictability). Another possibility would be to make the bigram-word-bigram presentation appear more like a word-word-word presentation (but without using flanking words as this would increase the contextual predictability of the central word), as this might increase the level of lexical processing of the flanking information. One way to achieve this would be to add extra flanking letters outside the bigrams but 'fade' them out in an approximation of the acuity limitations when reading, as shown in Figure 40.

xxlt rock quxx

FIG. 40: The Context Flanking Letters Lexical Decision task with 'faded' external letters

The final experiment in this thesis will change direction slightly. The FLLD task provides a method for measuring the amount of processing of parafoveal information that occurs during word recognition, and Chapter 3 demonstrated that orthographic information impacts the lexical decision to the central word. However, the participant group in this demonstration consisted solely of readers who explicitly stated that they had no reading disorders. This is not the case for the large number of people who report reading difficulties, most of whom suffer from developmental dyslexia. There is now a large body of work into the nature of this disorder, including many disagreements as to its cause(s). One of these disagreements concerns the nature of parafoveal processing by dyslexic readers, with some researchers claiming that they process parafoveal information to the detriment of foveal processing, some claiming that they concentrate on foveal processing to the detriment of parafoveal processing, and some not considering this topic at all. The Orthographic FLLD task could provide a way to test between these theories by comparing the amount of priming of the central word obtained from orthographically related flanking bigrams in dyslexic and control readers.

Chapter 8
The Dyslexia Flanking Letters Lexical Decision Task
Introduction

Aims of the chapter

For those fortunate enough to read fluently, reading appears effortless and almost intuitive. Word recognition and lexical access during reading can be observed and modelled with relative ease by researchers, and reading forms a part of everyday life, an ability without which the world would seem confusing and uninformative. However, there is a significant proportion of the population for whom the task of reading becomes a chore due to their persistent inability to read with the same efficiency enjoyed by others. This reading disorder of developmental dyslexia has been widely studied by researchers from multiple disciplines, as elucidating its cause(s) has both theoretical and practical ramifications. It is with these consequences in mind that this experiment was designed, in an attempt to provide evidence for or against one recent theory as to the cause of dyslexia. Its place in this thesis comes from the suggestion that dyslexia is due to over-processing of parafoveal information by dyslexics, a claim that can be tested using the Orthographic Flanking Letters Lexical Decision task introduced in Chapter 3.

Developmental dyslexia: A brief introduction

Developmental dyslexia is a common reading disorder that occurs in around 5-10% of school-age children (e.g., Habib, 2000; Ramus, 2003). Symptoms include slow and effortful reading, word omissions and substitutions, uncertain spelling and mis-spelling, and laboured writing. Crucial to the definition is that these symptoms occur despite at least average intelligence and standard educational opportunities (World Health Organisation, 1993). Particular difficulties are encountered when distinguishing visually similar letters, acquiring whole-word representations and applying grapheme-phoneme conversion rules. Confusingly, research has shown that the dyslexic profile also includes poor memory, impaired information processing and motor skills, and a lack of dominant handedness (e.g., Nicolson & Fawcett, 1994), and dyslexia is often found to be co-morbid with disorders such as attention deficit hyperactivity disorder or ADHD (Kadesjö & Gillberg, 2001).

The number and severity of symptoms present in each dyslexic vary widely, and there have been several attempts to identify dyslexia sub-types based on these individual differences. For example, Manis, Seidenberg, Doi, McBride-Chang, and Petersen (1996) identified two sub-groups of dyslexics separated by a double dissociation on two tasks: phonological dyslexics were impaired in a phonological task only and surface dyslexics were impaired in an orthographic task only. This division roughly corresponds to that reported for acquired dyslexics, as surface dyslexics were relatively worse at exception word reading and phonological dyslexics were relatively worse at nonword reading, although both groups were impaired compared to a control reading group. Boder (1973) classified dyslexics as dysphonetic (impaired grapheme-phoneme conversion) and dyseidetic (impaired whole-word reading), whereas Bakker (1979) used the terms P-type and L-type to describe those who read slowly and those who read quickly but with more errors respectively. Both also allow for a mixed category, illustrating the difficulty faced by dyslexia researchers when categorising this complex disorder.

This complexity is also evident in the multiple theories that have been advanced to explain the causes of dyslexia. For many years the dominant theory was that dyslexia is due to a cognitive impairment in the representation, storage and retrieval of speech sounds. The speech errors, nonword and exception word reading difficulty, inability to identify rhymes and syllables and poor performance on phoneme manipulation tasks (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004) all support the phonological theory (see Snowling, 2000) which states that, as children, dyslexics fail to learn the letter-sound correspondences required in alphabetic language. Their lack of phonological awareness disrupts reading flexibility from an early age. This theory also claims that the heritability of dyslexia (a dyslexic has up to 50% probability of passing it on to a child) is due to an inherited phonological deficit, possibly caused by disruption of left-hemisphere cortical regions responsible for phonological processing (e.g., Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Paulesu et al., 2001). Several studies have reported an increase in reading ability for children following a phonological awareness training programme (e.g., Hatcher, Hulme, & Ellis, 1994).

Phonological processing is clearly an issue for dyslexics: a recent large-scale study by Ramus et al. (2003) recorded a 100% incidence of a phonological processing deficit, and the phonological theory underpins most diagnostic and intervention efforts. However, some researchers now question whether this single explanation can account for the multiple and varying deficits exhibited by dyslexics. Wolf and Bowers (2000) outline the evidence for the Double-Deficit Hypothesis (Wolf & Bowers, 1999) which characterises both phonological awareness and naming speed as independent causes of reading dysfunction. This theory stems in part from dyslexics' poor performance on the Rapid Automatised Naming task (RAN; Denckla & Rudel, 1974) which measures continuous serial letter naming speed. In general, researchers opposed to the phonological theory accept that phonological impairments are a key part of dyslexia, but contend that they are not, in themselves, a cause of the disorder and can be subsumed under a more general sensorimotor deficit theory.

Three separate sensorimotor processing deficits have been identified. The most prominent of these is the magnocellular visual dysfunction (Stein & Walsh, 1997) which contends that the magnocellular pathway of the visual system is disordered. This pathway is responsible for fast and transient visual information processing, and studies have indicated both anatomical and functional impairments to this system in dyslexics (Lovegrove, Bowling, Badcock, & Blackwood, 1980; Livingstone, Rosen, Drislane, & Galaburda, 1991). For example, Cornelissen, Richardson, Mason, Fowler, and Stein (1995) showed that most dyslexics have reduced visual motion sensitivity which relies on the magnocellular pathway. The magnocellular visual theory claims that these slight deficits affect the posterior parietal cortex which plays a role in controlling eye movements; this is evidenced in the binocular instability and visual confusions reported by dyslexics (Stein & Walsh, 1997).

The second sensorimotor theory is that dyslexics suffer from impaired auditory processing, particularly for rapidly presented sounds (Tallal, 1980), leading to a reduced ability for speech processing. This impairment has been demonstrated using a variety of tasks including temporal order judgement (e.g., De Martino, Espesser, Rey, & Habib, 2001), discrimination of sound frequency (e.g., Amitay, Ahissar, & Nelken, 2002) and gap detection (e.g., Chiappe, Stringer, Siegel, & Stanovich, 2002). From a remedial perspective, Tallal et al. (1996) presented dyslexic children with acoustically enhanced speech and temporal processing training over the course of four weeks and found that they made gains in speech and language processing equivalent to two years during this time.

Lastly, the motor control difficulties frequently observed in the dyslexic population led to the motor theory, or more specifically the cerebellar theory. Dyslexics' difficulties with reading, writing and spelling, as well as with balance, co-ordination and time estimation can all be seen as evidence of a cerebellar dysfunction (Nicolson, Fawcett, & Dean, 2001) leading to a difficulty with skill automisation.

These three theories have been unified under the general magnocellular theory (Stein, 2001), in which disordered magnocellular pathways lead to sensory impairments in the visual and auditory domains, the latter of which gives rise to phonological processing difficulties, with the cerebellum affected via the posterior parietal cortex. This theory follows the suggestion of Coltheart and Jackson (1998) that defining dyslexia in terms of its distal causes (such as insufficient reading tuition) is less useful than exploring more proximal causes (such as which reading sub-systems are impaired). The magnocellular theory has brought fresh impetus to the field of dyslexia research, but proponents of the phonological theory question whether magnocellular deficits are sufficiently prevalent in the dyslexic population for it to suffice as an explanation, and there is the additional issue of establishing a causal link between these deficits and the reading impairment central to the disorder (see Ramus, 2003). Ultimately, the decision as to which theory is most promising depends on the individual researcher's decision to pursue a cognitive, biological or genetic explanation, each of which almost certainly contains some merit.

Parafoveal processing in dyslexia: Over-processing

A recent theory that does not fall under the umbrella of phonological or magnocellular-type theories is that of Geiger and colleagues, concerning dyslexics' use of parafoveal information while reading. The typical finding when testing readers' perception of letter strings at increasing parafoveal eccentricity from the point of fixation is that letter identifiability decreases with increasing eccentricity in a linear fashion (the Aubert-Foerster function); this follows the general pattern of a linear relationship between minimum angle of resolution and eccentricity (e.g., Jacobs, 1979). Intriguingly, research by Geiger and Lettvin (1987) into peripheral letter recognition revealed a sub-group of participants who were considerably better at recognising letters at large eccentricities from fixation. Upon further questioning they found that these participants were all linked by a prior diagnosis of dyslexia; the interest in this finding stems in part from the finding of an advantage for dyslexics for letters presented beyond 5° of eccentricity.

Perry, Dember, Warm, and Sacks (1989) raised several methodological concerns with this work, including their small sample sizes and use of a blocked presentation design that allowed participants to anticipate the upcoming trial condition; despite these concerns, following improvements to the design they replicated the original finding. The initial work by Geiger and Lettvin (1987) was extended by Geiger, Lettvin, and Zegarra-Moran (1992) who compared the distribution of probability of recognising a letter at varying eccentricities from a central reference letter. This distribution, which they termed the form-resolving field (FRF), was larger in dyslexics as they exhibited a greater ability to recognise letters at the edge of vision, but performed less well than the control readers at small eccentricities. The FRF of dyslexics was not only wider than that of normal readers, but was asymmetrically extended in the direction of reading. These effects are similar across different sub-types of dyslexia (Lorusso et al., 2004) but the FRF's of dyslexic children are less asymmetric than those of adults (Geiger, Lettvin, & Fahle, 1994).

Geiger et al. (1992) hypothesised that dyslexics' relatively poor performance for centrally presented letters was due to lateral masking. Lateral masking is the process by which visual stimuli become obscured when surrounded by other stimuli (e.g., Bouma, 1970). For example, if a single letter is presented in peripheral vision its form remains clear, but if it is presented as part of a word its form becomes obscured, with the horizontal area of identifiability for embedded letters reduced to approximately one-quarter that of isolated letters. In normal readers, lateral masking is prevalent in peripheral vision: items in the centre of vision are easily distinguished whereas items in the periphery are easily confused. Geiger et al. (1992) suggested that the lateral masking that occurs for normal readers in peripheral vision might occur in central vision for dyslexics, providing a psycho-physiological explanation for the disorder, although the exact eccentricities that bound 'central' and 'normal' are not defined. In order to test this hypothesis they assessed performance of letter identification when presented as part of a string at different eccentricities, and found a similar pattern as for the isolated letters: dyslexics exhibited more lateral masking at lower eccentricities and less lateral masking at higher eccentricities than control readers. Geiger and Lettvin (2000) suggested that in normal reading lateral masking, or 'visual crowding', serves to actively suppress less important peripheral information and highlight the fixated material, but that in dyslexics this mechanism is not effective. The reduced peripheral lateral masking in dyslexia renders parafoveal words almost as salient as the fixated word, and thus disrupts the reading pattern. Geiger and colleagues (Geiger et al., 1992; 1994; Geiger & Lettvin, 1997; 2000) even suggested that a remedial activity for dyslexia (in both adult and child readers) is to read through a hole cut in a card in order to restrict the information available in the parafovea; this then reduces the asymmetry of the FRF. They report the case of 4 dyslexics who, following daily practice at reading within a 'window', exhibited reduced FRF's and marked improvement in reading skills.

Parafoveal processing in dyslexia: Under-processing

However, several groups of researchers have disputed this set of findings and their implications. Goolkasian and King (1990) and Klein, Berry, Briand, D'Entremont, and Farmer (1990) noted several flaws with the work by Geiger and Lettvin (1987) including the consistent presentation of the peripheral letters to the right of fixation, the increased stimulus exposure for dyslexics and the requirement for participants to report both the foveal and peripheral letters (so that if they were unsure of the identity of the peripheral letter they could simply repeat the foveal letter). Following adjustments to the task to remove these methodological concerns, both groups recorded no interaction between reading ability and letter eccentricity on letter identification levels, and Goolkasian and King (1990) recorded improved performance by the control readers at every eccentricity. Both groups concluded that the improved letter recognition at larger eccentricities reported by Geiger and Lettvin (1987) was due to poor methodology, and Klein et al. (1990) suggested that dyslexics were able to exploit this methodology to improve their performance and conceal their reading difficulties via attentional or fixation strategies.

There is, in fact, some evidence to suggest that dyslexics have greater problems than controls in processing parafoveal information. Bouma and Legein (1977) found that dyslexic children exhibited greater lateral masking than age-matched controls. Whereas both groups exhibited similar high rates of recognition for isolated letters in both foveal and parafoveal view the rate of recognition decreased substantially more for dyslexics when the embedded letters were presented parafoveally than in foveal vision, although as the maximum eccentricity employed was below 5° it is possible that dyslexics' recognition rates would have improved for letters presented further from fixation.

In a comprehensive investigation into the nature of lateral masking, Pernet, Valdois, Celsis, and Démonet (2006) used isolated and embedded letters from several orthographic systems presented at three different eccentricities to dyslexic and control readers. The dyslexics demonstrated both impaired performance for the isolated words and stronger lateral masking effects than the control participants, leading the authors to suggest that an underlying problem with visual attention for dyslexics is exacerbated by the presence of multiple visual units in an embedded letters presentqation. This suggestion is formalised in the visual attention (VA) span deficit hypothesis of Bosse, Tainturier, and Valdois (2007) that states that the number of elements in a multi-element array that can be processed in parallel is reduced for dyslexics. Following the finding that VA span is a predictor of reading ability independent of phonological skills the authors proposed that a VA span deficit can be a separate cognitive cause of dyslexia, forming part of a multi-factor view of the disorder. Pernet et al. suggested that as the magnocellular system is known to play a role in visual attention and processing of flanked items this cognitive difficulty could be explained by the general magnocellular deficit theory of dyslexia.

One final piece of evidence indicating that dyslexics have difficulty in processing parafoveal items comes from the reading literature. Rayner, Murphy, Henderson, and Pollatsek (1989) used the 'moving window' technique to establish that the perceptual span for dyslexics is approximately two-thirds the size of that of normal readers, as their reading patterns are typical of a window of two words rather than the three-word window required for normal readers. However, Rayner, Pollatsek, and Bilsky (1995) noted that this finding does not necessarily mean that dyslexics are less successful at processing parafoveal information; instead, they point to evidence showing that the perceptual span is decreased when readers come across difficult words (Henderson & Ferreira, 1990), thus suggesting that it is simply dyslexics' difficulty in processing the current word that causes this apparent parafoveal anomaly.

The current experiment

As discussed above, there exists some controversy as to the amount of parafoveal processing of visual stimuli that occurs during dyslexic reading, and whether over- or under-processing of parafoveal information contributes to the reading disturbance that characterises developmental dyslexia. One simple method for assessing the amount of processing of parafoveal information is to compare the reaction times to stimuli when related information is, or is not, presented in parafoveal vision. More specifically, do dyslexics receive more or less priming than control readers from orthographically related parafoveal letters in a centrally presented lexical decision task? This thesis has already established that normal readers produce faster responses to a word when it is flanked by letters derived from that word using the Orthographic FLLD task (Chapter 3), and this chapter extends this finding by adding the comparison with a disordered reading population. Figure 41 is a reminder of the paradigm and its three conditions. This experiment is a direct replication of the experiment presented in Chapter 3.

ro rock ck	*(Adjacent)*
ck rock ro	*(Reversed)*
le rock sh	*(Unrelated)*

FIG. 41: The Orthographic Flanking Letters Lexical Decision task

Background tests

In order to ensure that any differences recorded between the control and dyslexic reading groups can be attributed to this reading disorder, a series of cognitive tests will be conducted on both groups. Dyslexia is characterised by reading difficulties, so the test series will include a test of word reading and exception word reading. More specifically, dyslexia produces a deficit in phoneme manipulation, so a non-word reading and spoonerism production task will be included to test phonological decoding and awareness respectively. A further deficit associated with dyslexia is poor verbal short-term memory, which will be assessed via digit repetition. As the definition of dyslexia states that IQ level is not a cause of the disorder, two IQ tests will be administered to ensure that there is no confound. One of these will be a test of non-verbal IQ and one will involve participants' knowledge of vocabulary.

Predictions

Two basic predictions as to the results of this experiment are as follows: that dyslexics and control readers will both receive some priming from the related letters Adjacent and Reversed conditions, and therefore produce faster lexical decision responses; and that dyslexics will produce slower responses than the controls in all three conditions. However, it is the pattern of responses and interaction between flanking letters condition and reading ability that differs depending on the three theories of parafoveal processing in dyslexia. Geiger and colleagues (e.g., Geiger et al., 1992; Geiger & Lettvin, 2000) claim that dyslexics cannot suppress parafoveal information when reading. If this is true then the prediction follows that dyslexics will receive relatively more priming from the related flanking letters compared with control readers. If, however, dyslexics have greater difficulty than control readers in processing parafoveal information (e.g., Bosse et al., 2007; Pernet et al., 2006) then they should receive relatively little priming from the related flanking letters and their responses in these conditions should be relatively slower than would otherwise be expected. There also exists the third prediction that parafoveal processing plays no specific role in dyslexia, and that there will be no interaction between flanking letters condition and reading ability. Such a prediction comes from the suggestion by Rayner et al. (1995) that any difficulty that dyslexics exhibit for parafoveal processing stems only from foveal processing difficulties reducing the perceptual span.

Method

Participants

A total of 48 native English speakers were tested, of whom 24 had been diagnosed as dyslexic and 24 reported no difficulties with language processing. The mean ages of the two groups were 23 years (SD = 4.0) and 22 years 6 months (SD = 4.4) respectively; this did not differ significantly between the groups [$t(46) = 0.41$, *ns*]. There were 14 female and ten male participants in the dyslexic group and 15 female and nine male participants in the control group. Three of the dyslexics were rated as left-handed on the EHI (Oldfield, 1971); all other participants were rated as right-handed.

Materials

These were identical to those used in the Timed FLLD experiment: 144 words and non-words flanked by bigrams either derived from the central word (Adjacent and Reversed conditions) or containing none of the same letters as the central word (Unrelated condition).

Design

This experiment involved both the 3x2 within-subjects design of the Timed FLLD experiment and the additional variable of reading ability (dyslexic vs. control) to form a mixed 3x2x2 design. The 12 versions of the experiment described in the Timed FLLD experiment were counter-balanced across each group of participants.

Procedure

This was identical to the procedure carried out for the Timed FLLD experiment.

Data selection

There were a few deviations from the data processing method detailed for the Timed FLLD experiment. One control participant's data were discarded due to the large number of errors recorded (39%) and replaced by another participant. Calculation of the outliers was carried out separately for the dyslexics and controls as their mean reaction times were likely to differ. The accuracy scores were out of 24 for participants and out of 8 for items. The items analyses were incomplete due to some items having no correct responses that were not removed as outliers; however, this is less of an issue for LME analyses than for F1 and F2 analyses.

Language and IQ tests: Word processing

In addition to the experiment described above both groups of participants were evaluated on a range of tests designed to investigate language and cognitive abilities. These tests covered a full range of advanced word and phoneme processing and verbal ability, as well as two IQ components critical to the definition of developmental dyslexia. The tests used plus their remit, administration and scoring are described below.

The word processing section of The Wide Range Achievement Test (3rd edition; Wilkinson, 1993) or WRAT-3 is designed to test for word recognition. The participant read aloud from a card of printed words which increased in length and difficulty and were awarded a score according to the WRAT-3 guidelines depending on how many were correctly pronounced. Knowledge of exception words (those whose pronunciation or spelling is irregular such as *yacht*) was tested by a computer presentation of isolated exception words of increasing length that the participant read aloud (Wile & Borowsky, 2004). Words were presented in black size 12 Arial font on an off-white screen using the programme E-Prime on a PC. Scoring was out of 44 with one point per correct pronunciation.

Language and IQ tests: Other verbal abilities

Phonological manipulation was tested in two ways: phonological decoding with a non-word reading test (Manis et al., 1996) and phoneme awareness with a spoonerisms task (Hatcher, Snowling, & Griffiths, 2002). Administration of the non-word task was identical to the exception word task above except that the maximum score was 45. For the spoonerisms task the experimenter read aloud the first and last names of famous people and the participant was required to repeat them within approximately 10 seconds with the initial phoneme from each word swapped around. One point was awarded per correct word up to a maximum of 24 points. Finally, verbal short-term memory was assessed with a forward and backward digit repetition task (Miles, 1993) in which the participant repeated sets of numbers of increasing length, read aloud by the experimenter, until they were no longer accurate after two attempts. Two points were awarded for correct repetition on attempt one and one point for correct repetition on attempt two, up to a maximum of 18 points; this system was based on the Wechsler Adult Intelligence Scale – 3rd edition scoring system (WAIS-III ; Wechsler, 1992) but attempt two was omitted if attempt one was successful.

Language and IQ tests: IQ

Two sections from the WAIS-III (Wechsler, 1992) were included in this battery. The block design task for assessing non-verbal IQ required participants to copy 3-D designs printed on cards using a set of blocks. Both the complexity of the designs and the number of blocks available increased over the series of trials. Each trial was conducted under time pressure and points were awarded according to the time taken to complete each design according to the WAIS-III scoring system. A non-verbal assessment of IQ is the intuitive method for ensuring that intelligence does not act as a confound for symptoms of a language disorder. However, Goswami (2003) pointed out that an additional confound could come from group differences in verbal knowledge, such as vocabulary. In order to rule out this possibility the vocabulary section of the WAIS-III was also included. Vocabulary was tested with the participant's verbal description of the meaning of a series of words of increasing complexity with 0, 1 or 2 points awarded per description according to the scoring criteria of the WAIS-III.

Half of each participant group completed these tests first and half completed the experiment first. They took approximately 40 minutes to complete and the order of administration was counter-balanced using a Latin Square design. One potentially interesting test that was omitted was the spelling section of the WAIS-III but as this takes approximately 20 minutes to complete it was felt that participant fatigue would be an issue.

Results

Language and IQ tests

Table 20 shows the mean scores and results of the independent-samples t-tests carried out to compare the performance of dyslexics and controls on the background tests. The exception word task and digit recall were accidentally each omitted from the battery for one participant: these omissions are reflected in the reduced degrees of freedom for these tests.

TABLE 20

Mean scores (and standard deviations) of the controls and dyslexics on the clinical tests

Tasks	Controls	Dyslexics	*t*-values (df)	*p*-values
Word recognition	113.2 (5.8)	102.9 (12.8)	3.6 (46)	0.001
Exception word reading	42.1 (1.0)	40.3 (3.0)	2.7 (45)	0.01
Non-word reading	42.6 (1.6)	38.7 (5.1)	3.6 (46)	0.001
Spoonerisms	21.6 (3.4)	18.5 (6.5)	2.1 (46)	0.05
Digit memory	15.0 (2.7)	13.7 (3.1)	1.5 (45)	*ns*
WAIS Vocabulary	11.3 (1.3)	10.3 (1.2)	2.8 (46)	0.01
WAIS Block design	13.2 (2.6)	13.4 (2.8)	0.3 (46)	*ns*

Overall, the results of the comparison indicate that the dyslexics follow the typical pattern of significantly lower scores for the language tasks but not for the IQ tasks compared with the controls. They exhibited poorer performance on the word processing (word recognition and exception word reading) and phonological manipulation tasks (non-word reading and spoonerisms) but comparable performance on the non-verbal IQ task (block design) which is arguably the better indicator of IQ given the nature of the disorder. Indeed, it could be argued that vocabulary size is likely to be reduced in dyslexics given the increased difficulty of reading widely for this group; this would explain the significantly reduced vocabulary scores for the dyslexic group. The other non-typical finding is that dyslexics were no worse at the digit memory task than the controls. It is not clear why this should be the case but it is possible that either dyslexics' verbal short-term memory is only impaired for language tasks, or that the high education levels of the student samples led to a floor effect for a simple task.

Reaction times

As a comparison of Tables 21 and 22 and Figures 42 and 43 shows, the dyslexics' reaction times were approximately 70 msecs slower than those of the controls. High frequency words were always responded to more rapidly than low frequency words, and the Adjacent bigram condition was always responded to most quickly, then the Reversed condition, with the Unrelated condition always the slowest.

TABLE 21

Mean reaction times (and standard deviations) in milliseconds as a function of flanking bigram type and word frequency for the dyslexics

	Flanking bigram type		
	Reversed	Adjacent	Unrelated
Reaction time (milliseconds)			
High frequency words	726.7 (119.5)	706.8 (123.6)	741.0 (104.8)
Low frequency words	886.6 (147.4)	859.2 (132.8)	909.6 (133.5)

TABLE 22

Mean reaction times (and standard deviations) in milliseconds as a function of flanking bigram type and word frequency for the controls

	Flanking bigram type		
	Reversed	Adjacent	Unrelated
Reaction time (milliseconds)			
High frequency words	667.7 (123.0)	657.7 (109.4)	681.8 (118.2)
Low frequency words	791.1 (120.5)	788.1 (107.5)	817.6 (119.7)

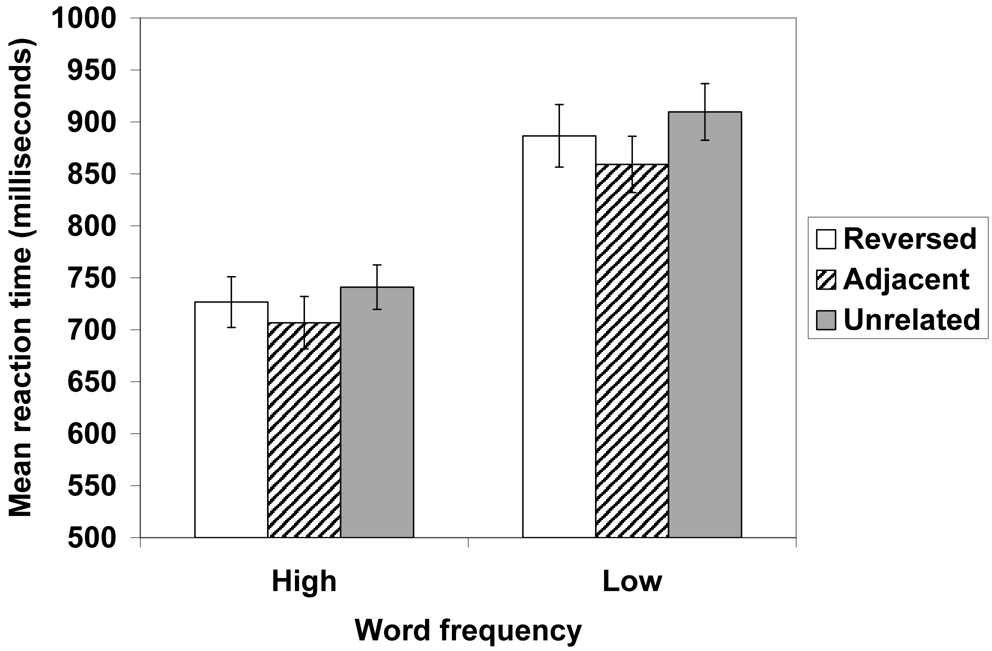

FIG. 42. The effect of flanking bigram condition and word frequency on lexical decision reaction times by the dyslexics; error bars indicate standard error of the mean

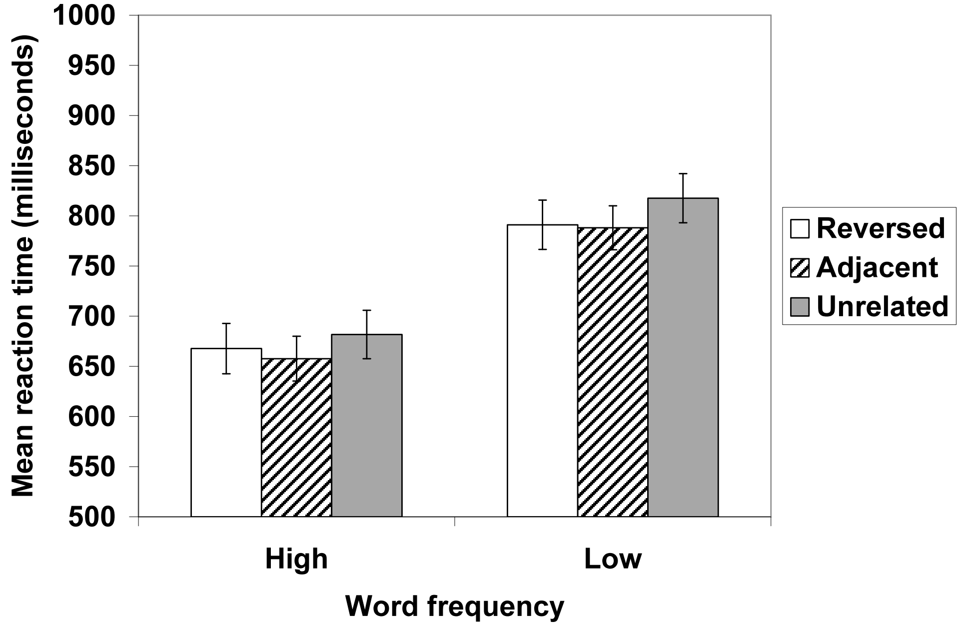

FIG. 43. The effect of flanking bigram condition and word frequency on lexical decision reaction times by the controls; error bars indicate standard error of the mean

A 3-way mixed ANOVA (2x2x3) found a main effect of reading ability [$F_1(1,46) = 4.882$, $p < 0.05$; $F_2(1,274) = 85.786$, $p < 0.001$], a main effect of word frequency [$F_1(1,46) = 340.979$, $p < 0.001$; $F_2(1,274) = 351.854$, $p < 0.001$] and a main effect of bigram type [$F_1(2,92) = 11.047$, $p < 0.001$; $F_2(2,548) = 5.148$, $p < 0.01$]. Post-hoc paired-samples t-tests tests with a Bonferroni correction indicated that there was a significant difference between the Adjacent and Unrelated conditions [$t_1(47) = 6.04$, $p < 0.001$; $t_2(279) = 3.09$, $p < 0.01$] as reaction times were significantly faster in the Adjacent bigram condition. Additionally, there was a marginally significant difference between the Reversed and Unrelated conditions by participants [$t_1(47) = 2.38$, $p = 0.065$] but not by items [$t_2(279) = 1.63$, *ns*] and no difference between the Adjacent and Reversed conditions [$t_1(47) = 1.90$, *ns*; $t_2(279) = 1.65$, *ns*]. Analyses by participants did not show any significant interactions, but by items there was a significant interaction between reading ability and word frequency [$F_2(1,274) = 4.152$, $p < 0.05$]. This was because the dyslexics' reaction times were disproportionately increased by low frequency words.

An LME analysis also showed that there were significant main effects of reading ability [$F(1,5847.77) = 167.79$, $p < 0.001$], word frequency [$F(1,127.64) = 279.56$, $p < 0.001$] and bigram condition [$F(2,5846.48) = 9.33$, $p < 0.001$]. Post-hoc t-tests again showed that words in the Adjacent condition were responded to more rapidly than those in the Unrelated condition [$t(5848.79) = 4.31$, $p < 0.001$]. There was also a marginally significant difference between the Reversed and Unrelated conditions [$t(5848.49) = 2.37$, $p = 0.053$] but not between the Adjacent and Reversed conditions [$t(5842.18) = 1.95$, *ns*]. This analysis confirmed the significant interaction between reading ability and word frequency [$F(1,5846.36) = 7.12$, $p < 0.01$] although no other 2- or 3-way interactions reached significance.

Accuracy scores

TABLE 23

Mean accuracy scores (and standard deviations) as a function of flanking bigram type and word frequency for the dyslexics

	Flanking bigram type		
	Reversed	Adjacent	Unrelated
Accuracy (out of 24)			
High frequency words	22.7 (1.4)	22.8 (1.6)	22.3 (1.8)
Low frequency words	17.4 (3.8)	17.5 (3.9)	17.0 (3.7)

TABLE 24

Mean accuracy scores (and standard deviations) as a function of flanking bigram type and word frequency for the controls

	Flanking bigram type		
	Reversed	Adjacent	Unrelated
Accuracy (out of 24)			
High frequency words	23.3 (0.5)	23.6 (0.8)	22.9 (1.5)
Low frequency words	20.4 (2.0)	20.6 (2.7)	20.3 (2.5)

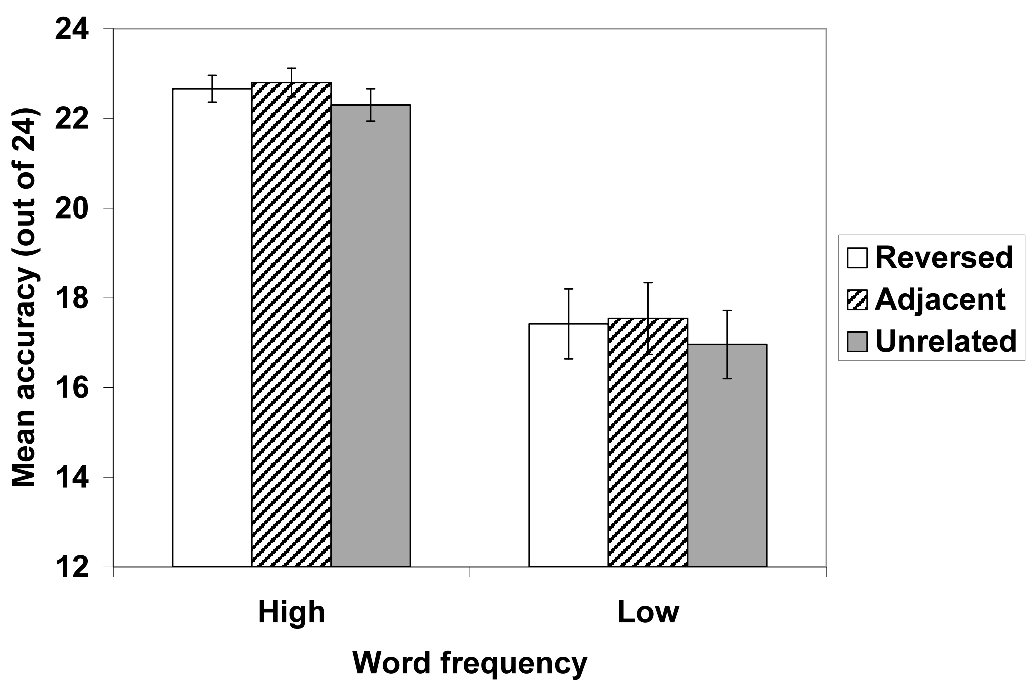

FIG. 44. The effect of flanking bigram condition and word frequency on lexical decision accuracy scores by the dyslexics; error bars indicate standard error of the mean

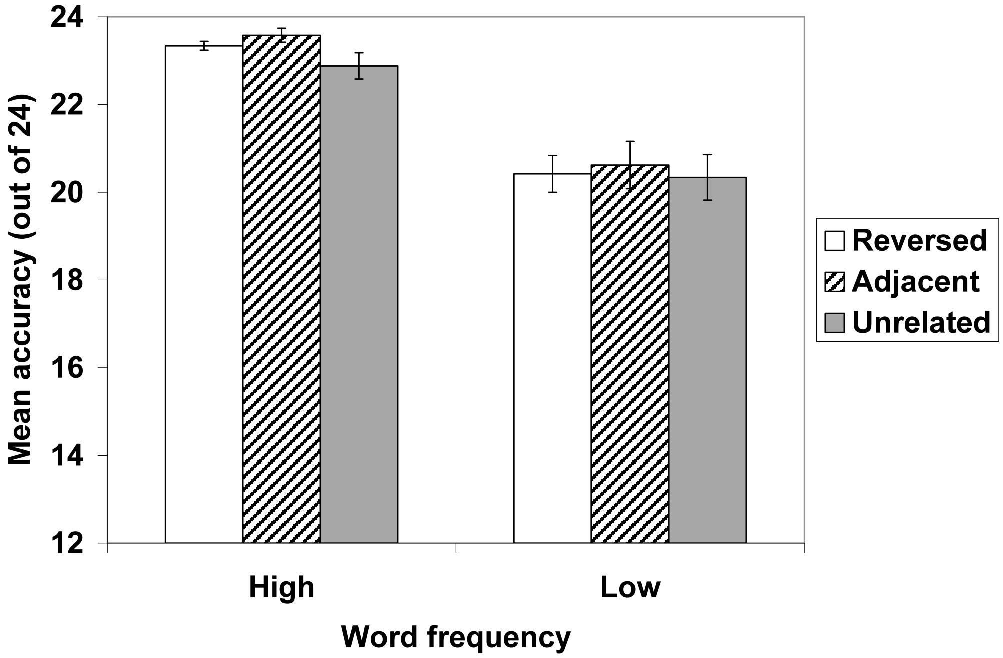

FIG. 45. The effect of flanking bigram condition and word frequency on lexical decision accuracy scores by the controls; error bars indicate standard error of the mean

A 3-way mixed ANOVA (2x2x3) found a main effect of reading ability [$F_1(1,46) = 14.752$, $p < 0.001$; $F_2(1,274) = 36.350$, $p < 0.001$] and a main effect of word frequency [$F_1(1,46) = 152.602$, $p < 0.001$; $F_2(1,274) = 138.153$, $p < 0.001$] on accuracy scores. By participants there was no main effect of bigram type [$F_1(2,92) = 2.293$, *ns*], although there was a significant interaction between reading ability and frequency [$F_1(1,46) = 14.274$, $p < 0.001$]. By items, there was a main effect of bigram type [$F_2(2,548) = 3.120$, $p < 0.05$], although post-hoc tests with a Bonferroni correction did not indicate significant differences between any of the bigram order conditions, and there was no interaction between reading ability and frequency [$F_2(2,548) = 0.511$, *ns*].

Discussion

Reading ability predictions

The two independent groups tested in this experiment were formed from those who suffer from the reading disorder of developmental dyslexia, and control readers of a similar age and level of education. The effortful word processing and phoneme manipulation characteristic of dyslexia were confirmed as being present only in the former group via a series of cognitive and language tests, and the influence of non-verbal IQ was ruled out. These groups were compared on their reaction times and accuracy scores on a lexical decision task, with the addition of flanking letters that were either related or unrelated orthographically to the central letter string under consideration. A recent theory as to the cause of dyslexia comes from work by Geiger and colleagues (e.g., Geiger & Lettvin, 1987) suggesting that dyslexics process parafoveal information more than normal readers due to incorrect lateral masking of foveal information, leading to poor reading skills. It follows from this theory that the identity of the flanking letters should influence dyslexics' responses in the lexical decision task more than it influences the control readers. Contrary to this is the prediction that follows from the visual attention (VA) span deficit hypothesis (Bosse et al., 2007) that states that the number of visual items that can be processed in parallel is reduced for dyslexics; from this it can be inferred that dyslexics should be relatively less affected by the flanking letters than the control readers.

Overall, the reaction times results for this experiment largely replicated those of the original Orthographic FLLD experiment. High frequency words were responded to more quickly than low frequency words, following the trend from the other experiments in this thesis and from the wider lexical decision literature. Responses were also more rapid in the Adjacent and Reversed conditions than in the Unrelated conditions, showing that when the flanking bigrams were orthographically related to the central word lexical decision times were faster than when the bigrams contained only unrelated letters. One slight discrepancy between these results and those reported in Chapter 4 is that the Adjacent bigrams condition produced slightly more priming than the Reversed bigrams condition, as demonstrated by the only marginally significantly faster reaction times in the Reversed condition than in the Unrelated condition. This implies that the related identity and order of the bigrams in the Adjacent condition led to increased priming in this condition compared with the related identity only of the bigrams in the Reversed condition, and could be seen as support for the existence of slot-based coding of letter inputs in word recognition. However, the difference between the reaction times in the Reversed and Unrelated conditions was very close to significance ($p = 0.053$), and additionally there was no significant difference between the Reversed and Adjacent conditions despite the order information present in the Adjacent condition only.

Turning to the differences between the two reading ability groups, unsurprisingly the dyslexics produced slower reaction times overall and demonstrated an additional deficit in processing low frequency words, as shown by the interaction between reading ability and word frequency. However, there was no hint of an interaction between reading ability and bigram condition, indicating that although their word processing is poorer dyslexics processed the flanking bigrams in the same manner as the control readers, and received the same level of priming from orthographically related parafoveal letters.

Supplementary analyses of accuracy scores supported some of the results outlined above: high frequency words were more likely to be correctly identified than low frequency words, and dyslexics' responses were less accurate than those of the control readers. The F1 analysis did not replicate the reaction time result of a main effect of bigram condition, although it was also the case in Chapter 4 that this main effect was only apparent in the reaction time measure and implies that accuracy of response is not sufficiently sensitive to detect this more subtle effect (while the items analysis yielded a significant main effect of bigram condition, this could not be teased apart in the post-hoc analysis). The interaction between reading ability and word frequency was also not replicated in the participants analysis, although its significance in the items analysis suggests that dyslexics' accuracy of response is disproportionately influenced by the lexical frequency of the attended word.

Implications for theories of dyslexia

The lack of an interaction between reading ability and bigram condition in the above results implies that altered parafoveal processing is not a core part of the disorder profile of dyslexia. This is in clear contrast to the substantial body of work presented by Geiger and colleagues (Geiger & Lettvin, 1987; 1997; 2000; Geiger et al., 1992; 1994; Lorusso et al., 2004) as evidence that dyslexics exhibit reduced peripheral lateral masking relative to controls. Their findings include a flatter Aubert-Foerster function for peripheral letter identification in dyslexics and improved reading skills for dyslexic children trained to read through a window. The current work does not support their theory that a non-optimal distribution of lateral masking is a psycho-physiological explanation for dyslexic symptoms or that improved letter recognition at larger peripheral distances is a non-reading marker of the disorder (Geiger & Lettvin, 2000). This experiment is instead in line with that of several researchers who have questioned the conclusions of Geiger and colleagues due to methodological concerns (Goolkasian & King, 1990; Klein et al., 1990).

However, the current work is also in contrast to the VA span deficit hypothesis (Bosse et al., 2007) as this proposes that the limited parallel processing abilities of dyslexics constitutes a cognitive cause of dyslexia, separate from the more commonly reported phonological difficulties. According to this theory, dyslexics should have received less priming from orthographically related flanking letters than the control readers, but there was no evidence for the veracity of this prediction either. What, then, can safely be claimed with regard to parafoveal processing and its relationship to dyslexia?

The most probable link between parafoveal processing and dyslexia seems to be that proposed by Rayner et al. (1995). During their earlier investigation of the size of perceptual span of dyslexics, they had established that it was only about two-thirds the size of the span of normal readers (Rayner et al., 1989). This could easily add to the argument that limited parafoveal processing is a contributor to dyslexia, but Rayner et al. (1995) instead proposed that under a foveal load framework (Henderson & Ferreira, 1990) it is dyslexics' core difficulty with foveal information processing that causes the narrowing of their perceptual span, leading to the side issue of a peripheral information processing deficit. Support for this proposal comes from the interaction between reading ability and word frequency in the current work due to dyslexics' disproportionately slow response times to low frequency words. However, this theory would also predict a three-way interaction between reading ability, bigram condition and word frequency, with reduced priming from related flanking bigrams (reduced perceptual span) for low frequency words (increased foveal load) for dyslexics only. This interaction was not observed in this experiment, but the foveal load hypothesis still seems the most likely way to account for the results obtained by Geiger and colleagues.

This proposal might additionally explain the lack of interaction between reading ability and bigram condition in this experiment. Lexical decision is not a demanding task, especially considering the high education attainment level of all participants. A negative result is always less satisfying than a positive one, and it would be interesting to test the limits of dyslexics' seemingly unaffected parafoveal processing capabilities with a more challenging test of foveal processing. This could involve a reading paradigm with a boundary change to test parafoveal orthographic priming such as that employed in Chapter 4, or a single word task requiring phoneme manipulation. Measurement of the participants' form-resolving field (FRF) via eccentric letter identification would also provide a link between the psychophysical measurements reported by Geiger and colleagues and the ecological reading and word identification deficits that are key to the definition of dyslexia.

Chapter 9
General Discussion

Aims of the thesis

The aim of this thesis was to investigate priming from parafoveal information during isolated word recognition and reading, in order to explore the possibility that readers take advantage of the information available outside the current fixation point in a way that does not have a strong analogue in speech processing. One way in which this aim was addressed was via the introduction of spatial priming, in which primes are presented alongside the target. This is in contrast to the usual priming demonstrations involving presentation of the target following presentation of the prime, which can be thought of as temporal priming. Spatial priming was implemented in both lexical decision and eye-tracking experiments in the course of this thesis. The majority of the experiments (Experiments 1-4, 6) investigated orthographic-level priming from parafoveal information, but Experiment 5 instead used a different version of spatial priming to assess the effect of the letter context provided by flanking letters during isolated word recognition.

This thesis set out to address issues within both word recognition and text reading, and to tie the two topics together in a way that rarely occurs. Experiment 1 therefore presented the lexical decision version of the orthographic spatial priming task to investigate slot-based coding in models of isolated word recognition, and Experiment 6 repeated this task with the added participant group of people with dyslexia to investigate parafoveal processing in this well-known reading disorder. Experiments 2 and 3 turned to eye-tracking of orthographic spatial priming to investigate the distribution of attention during reading. Perhaps most interestingly, Experiments 4 and 5 combined aspects of both topics. Experiment 4 utilised a paradigm that could test for both slot-based coding during lexical access and the distribution of attention during reading, and Experiment 5 investigated whether our typical perception of words in the flow of text affects our reactions to words in isolation.

Experiment summaries

Six experiments were carried out for this thesis to investigate the reading and word recognition topics outlined above. The first of these introduced the Orthographic Flanking Letters Lexical Decision (FLLD) task initially devised by Dare and Shillcock (2005). It involves a lexical decision to a word flanked by bigrams that are derived from or orthographically unrelated to the central word in order to determine whether there is orthographic priming from peripherally presented letters. This paradigm provides a test of whether foveal and parafoveal letters are processed in parallel. Thirty-six participants responded to 144 four-letter words flanked by orthographically related or unrelated bigrams, with the results demonstrating significantly reduced response durations in the related bigrams conditions. More intriguingly, there was no difference between the priming received from the Adjacent (*wo word rd*) and Reversed (*rd word wo*) conditions despite the amended order of the letters in the Reversed condition. This provides support for recent theories of letter input processing in word recognition that propose greater importance for correct letter identity than letter order (Davis & Bowers, 2006; Gómez et al., submitted; Grainger et al., 2006; Shillcock et al., 2000; Whitney, 2001), in contrast to earlier work advocating slot-based coding as the letter input method (Coltheart et al., 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap et al., 1982; Seidenberg & McClelland, 1989). The FLLD task falls within the group of studies employing primes containing transposed letters whose priming efficacy implies that a more flexible letter input coding scheme is required (Davis & Bowers, 2006; Guerrera & Forster, 2008; Perea & Lupker, 2003, 2004; Whitney & Cornelissen, 2008).

As well as providing evidence against the use of slot-based letter input coding in word recognition, the FLLD task has the additional benefit of providing a link between the work on isolated word effects and text reading effects, a link whose importance for both areas is increasingly widely recognised (Radach & Kennedy, 2004). Spatial priming involving the simultaneous presentation of target and prime is the isolated word analogue of the parafoveal-on-foveal effects reported in text reading (e.g., Kennedy, 1998), and the demonstration of parallel orthographic processing during lexical access of a single word suggests that this might also occur during reading in the form of an orthographic parafoveal-on-foveal during text reading. Such an effect has, in fact, been demonstrated by Inhoff, Starr, et al. (2000), albeit it in a limited fashion in a paradigm involving the overt repetition of the target word. The importance of such an effect lies in its ability to distinguish between serial (e.g., Reichle et al., 1998) and parallel (e.g., Engbert et al., 2002) processing models of eye movement control during text reading, as only the latter of these predicts the existence of parallel orthographic processing. Experiments 2-4 of this thesis therefore turned to eye-tracking of participants as they read sentences containing target words flanked by orthographically related words, in an attempt to establish whether parallel orthographic priming effects also occur during text reading.

Experiment 2 therefore required 30 participants to read 69 sentences containing a target word followed by a parafoveal prime word that was either a repetition of the target word or a control word that contained none of the letters of the target word but was of the same word length and similar lexical frequency. In order that participants not notice this repeated word (unlike in Inhoff, Starr et al., 2000) the boundary paradigm (Rayner, 1975) was employed such that when the right eye crossed the pixel to the right of the target word the parafoveal prime word was replaced by a word of the same length that made sense in the context of the rest of the sentence. Eye-tracking revealed orthographic priming from the repeated parafoveal word, as indicated by shorter first-pass viewing times for the target word in this condition. This result is evidence in favour of the simultaneous orthographic processing of word n and word n+1, a result that is incompatible with a model of text reading relying on serial shifts of attention and thus serial orthographic processing such as E-Z Reader (e.g., Reichle et al., 1998).

Thus far, the results from Experiments 1 and 2 are in favour of parallel orthographic processing and models such as SWIFT (e.g., Engbert et al., 2002) that claim up to four words around the fixation point are processed concurrently. According to the gradient of attention implemented in SWIFT, one of these words includes that to the left of fixation, or word n-1. This extended perceptual span is based on experimental results and corpus analyses indicating that visual, orthographic and lexical properties of word n-1 are all apparent in the eye movement patterns of word n (Balota et al., 1985; Binder et al., 1999; Inhoff, Radach, et al., 2000; Kliegl, 2007; Kliegl et al., 2006; Pynte & Kennedy, 2006; Starr & Inhoff, 2004). Experiment 3 tested whether this parallel orthographic processing extends to word n-1 using a paradigm very similar to that of Experiment 2 but with the word replacement occurring for the word preceding the target word, once the target word was fixated. This time, however, there was no effect of target word repetition on target viewing durations, and it appears that even if word n-1 is processed once the eyes have moved to the next word, this processing does not impact the processing of the next word. This finding is in contrast to the predictions from a parallel processing perspective, probably due to the 'pull' of attention towards the right caused by English reading direction leading to more subtle effects of word n-1.

A potential criticism of the conclusions from Experiment 2 is that any priming of the target word from an identical word presented in parafoveal vision could come from low-level visual similarity between these words, rather than from orthographic overlap. This is an important distinction, as later versions of E-Z Reader (E-Z Reader versions 7+; Reichle et al., 2003) allow some parallel processing in the form of a low-level visual scan that the authors claim can account for parafoveal-on-foveal effects due to irregular orthography (Inhoff, Starr, et al., 2000; Starr & Inhoff, 2004). In order to rule out the possibility that the previous results could be attributed to visual similarity, Experiment 4 was a repetition of Experiment 2 but included a comparison of two parafoveal non-word primes formed by transposing or substituting the central letters of the target word. This meant that the former prime maintained a stronger orthographic relationship with the target word than the latter, while word shape was identical for both. Inclusion of these two primes also allowed for a test of whether slot-based coding is an appropriate letter input mechanism during lexical access whilst reading, following the logic that as slot-based coding involves the conjunctive coding of letter identity and order there should be equivalent levels of priming from both the transposed and substituted letters primes. This logic was also exploited by Johnson et al. (2007) in a parafoveal preview paradigm. The results yielded reduced gaze durations on the target word in the transposed condition compared to the substituted condition, with no difference between the durations in the transposed condition and an identical prime condition. This finding lends support to the conclusion from Experiment 2 that there is parallel orthographic processing during reading, and also the conclusion from Experiment 1 that letter identity can be processed independently of letter order. This experiment continues the fledgling investigation of how lexical access occurs during text reading, and in this respect can be seen as the complement to Experiment 1 which assessed the impact of letter context on isolated word processing.

Continuing the theme of linking isolated word recognition and text reading, Experiment 5 presented an amended version of the FLLD task in which the flanking bigrams were chosen to represent a more or less plausible letter context surrounding the target word. The probability of co-occurrence of two words in text is known as transitional probability (McDonald & Shillcock, 2003a, 2003b), which is a measure of the predictability of a word that does not depend upon semantic knowledge, and there exists some controversy as to whether or not these two aspects of predictability act independently (Frisson et al., 2005). The FLLD task provides a method for separating these variables by presenting only the letter-level contextual information without semantic interference. The results of Experiments 2 and 4 demonstrated clear support for the concept of parallel orthographic processing across multiple words, and the FLLD task acts as a test of whether this affects our responses to isolated words. The letter context in this experiment was constructed by utilising bigrams that were more likely to occur either preceding a word or following it than the other way around, to form a plausible and implausible bigram condition. However, the results of the lexical decision response durations indicated no difference between these conditions, undermining the possibility that parallel processing of words in text conditions our responses to words in isolation, although future work might reveal a different result.

Finally, Experiment 6 demonstrated the wide utility of the FLLD paradigm by comparing the performance of dyslexics and control readers on the orthographic version of the task. Of the many causes of dyslexia proposed by researchers (e.g., Nicolson et al., 2001; Snowling, 2000; Stein & Walsh, 1997; Tallal, 1980; Wolf & Bowers, 1999) a recent controversy in this area concerns dyslexics' use of parafoveal information while carrying out foveal processing. Geiger and colleagues (Geiger et al., 1992, 1994; Geiger & Lettvin, 1987, 1997, 2000; Lorusso et al., 2004) proposed that lateral masking processes deviate towards foveal vision for dyslexics, leading to unwanted distraction from peripheral information obscuring foveal processing. This was based on their finding of better letter recognition at large peripheral eccentricities for dyslexics compared to normal readers. However, Experiment 6 found no evidence of altered parafoveal processing for dyslexics in the form of more or less orthographic priming from parafoveal letters compared to control readers. While this does not support the work by Geiger and colleagues, it also does not support the contradictory theory of reduced parafoveal processing according to the visual attention span deficit hypothesis (Bosse et al., 2007). The most sensible conclusion seems to be that of Rayner et al. (1995) that if the parafoveal processing capabilities are altered in dyslexia, this is due to compromised foveal processing.

Theoretical implications: Parallel orthographic processing

The two main themes that run through the experiments carried out for this thesis concern lexical access. The first is whether there is serial or parallel processing of foveal and parafoveal orthographic information, and the second is the appropriateness of slot-based coding as a letter input mechanism. The remainder of this Discussion will set out the conclusions that can be drawn on these two topics based on the work carried out so far, and present ideas for future studies to supplement and enhance this work. The final section will discuss how these two topics can be combined in the meta-topic of how work on text reading and isolated word recognition can and should be brought together.

Starting with whether orthographic processing operates according to a serial or parallel mechanism during text reading, the clear conclusion from the results of Experiments 2 and 4 is that there is parallel processing of both the word being fixated, or word n, and the upcoming word, or word n+1. Experiment 1 (and Experiment 6) was the precursor to the eye-tracking carried out for these two later experiments, as it demonstrated that simultaneous presentation of orthographically related flanking letters speeds lexical processing of a fixated word, indicating that letter-level processing can take place across the visual field. The importance of this implication for text reading models comes from the conflict between those who contend that lexical processing during reading is serial, and only occurs for one word at a time, and those who support the theory that lexical access occurs in parallel, for every word within visual range at the same time. This latter position is clearly supported by the findings from Experiments 2 and 4 that used eye-tracking of natural reading to demonstrate that the orthographic properties of an upcoming word are able to influence the eye movement pattern recorded for the currently fixated word, a process that could only occur if words n and n+1 are processed concurrently.

This conclusion is in favour of models such as SWIFT (Engbert et al., 2002; 2005) in which lexical processing is distributed over four words around the fixation point with the saccade target chosen as the word with the highest level of activation at the point of saccade generation. This distributed processing gradient causes parallel processing and is the model's explanation for parafoveal-on-foveal effects. A recent version of the model (Richter et al., 2006) includes increased letter-level refinement and an account of landing-site errors, both of which allow it to reproduce human reading data with admirable accuracy. In contrast to this style of model is E-Z Reader (Reichle et al., 1998) that implements strict serial shifts of attention between words and thus confines lexical processing (including orthographic processing) to one word at a time. This model does not predict the occurrence of parafoveal-on-foveal effects as it has no way to account for lexical-level influences between words within a single fixation.

Thus far, this conclusion seems clear-cut and water-tight. Of course, this is not the whole picture, and there are both criticisms from supporters of serial processing and inconsistencies within the results of this thesis that need to be addressed. There are four major criticisms of parafoveal-on-foveal effects put forward by those who advocate serial processing (see Rayner, White, et al., 2003). The first of these is the use of non-naturalistic tasks such as a 'looks-means' judgement (e.g., Kennedy, 1998) rather than text reading; this was quickly corrected (e.g., Inhoff, Starr, et al., 2000; Underwood et al., 2000) and all three experiments within this thesis that investigated parafoveal-on-foveal effects employed a reading paradigm. The second criticism was the inconsistency of the findings due to the reports of null effects (Altarriba et al., 2001; Rayner et al., 1986; Schroyens et al., 1999; White & Liversedge, 2004) and reports of contradictory effects, sometimes within the same study (Hyönä & Bertram, 2004). In this thesis Experiments 2 and 4 produced the same result of reduced first-pass fixation durations on the fixated word when in the presence of orthographically related parafoveal stimuli, a result that is identical to that of Inhoff, Radach, et al. (2000) using a similar (albeit less plausible) paradigm. The clear theoretical reason for this finding – orthographic priming easing lexical access of the fixated word – has its precedent in the large body of work on priming effects (e.g., Evett & Humphreys, 1981; Forster & Davis, 1984; Kwantes & Mewhort, 2002).

Criticism number three is of those parafoveal-on-foveal effects that occur due to sub-lexical properties of the parafoveal word, such as the presence of unusual orthography (Inhoff, Starr, et al., 2000; Starr & Inhoff, 2004). Such effects can be accounted for by later versions of E-Z Reader (versions 7+, Pollatsek et al., 2006; Reichle et al., 2003; 2006) that include a pre-attentive visual scan that occurs in parallel across the low-level features of upcoming words. Unusual orthography in parafoveal vision could affect the current fixation without requiring attention to be allocated beyond the current word. Although unlikely, these later versions of E-Z Reader could account for the results of Experiment 2, as the visual similarity of the parafoveal word and the target word in the Repeated condition could serve to shorten fixation durations on the target word. Part of the remit of Experiment 4 was to prove that the results of Experiment 2 were due to orthographic-level effects, rather than visual effects, by comparing parafoveal stimuli whose visual similarity to the target word was closely matched but whose orthographic similarity was not. This is an important distinction: orthographic-level effects are firmly located at the L1 lexical stage of lexical access (Reichle et al., 2007), a stage that is dependent upon the allocation of attention that under an E-Z Reader framework is strictly serial. The results of Experiment 4 showed that only those parafoveal stimuli with a strong orthographic relation to the target word led to reduced viewing times on the target word. This result would only be predicted by a model that allowed parallel allocation of attention across the target and parafoveal stimuli simultaneously i.e., not by E-Z Reader.

This criticism suggests a potential further experiment that could be carried out to strengthen the claim that lexical processing, as well as sub-lexical processing, operates in parallel. In Experiment 4 the Transposed condition involved a non-word formed by altering the order of the letters of the target word. This could easily be extended to create pairs of orthographic neighbours of different lexical frequencies (e.g., *calm*/*clam* high/low versus *clam*/*calm* low-high), similar to the work on isolated word pairs by Vitu et al. (2004). The prediction is that if lexical processing follows a parallel model then the size and/or direction of parafoveal-on-foveal effects should be modulated by the relative frequencies of the two words. This would represent an improvement over the work by Vitu et al. (2004) as the words would be embedded in a sentence containing a boundary change to create as realistic a reading scenario as possible.

The final criticism levelled at parafoveal-on-foveal effects is that they could be due to mislocated fixations. The logic behind this argument is that if the properties of word n+1 are apparent during fixation on word n, this is because the fixation was mislocated on word n and it is in fact word n+1 that is undergoing scrutiny. This claim is based upon an analysis by Nuthmann et al. (2005) that yielded an estimate of 10% mislocated fixations in a typical reading pattern. It follows that parafoveal-on-foveal effects should only be recorded when the fixation on word n fell towards the end of the word, close to word n+1, as reported by Drieghe et al. (2008). However, this was not the case for the work by Inhoff, Radach, et al. (2000) on whose study Experiment 2 was based: they analysed the fixation pattern for the first part of word n separately from that of the last four characters of the word and produced identical results for both. Although separate analyses of the first and last parts of the target word were not possible for this experiment (as the target words were either four or five letters in length) it seems implausible that the clear effects of a repeated parafoveal word could be attributed to mislocated fixations that are estimated to occur only 10% of the time. Furthermore, mislocated fixations would produce parafoveal-on-foveal influences from properties of all levels of lexical processing, whereas Rayner and colleagues continue to insist that lexical level effects do not occur. Lastly, if mislocated fixations on word n are reflecting some property of word n+1, then that property should produce a similar effect for both words. This logic does not explain the finding by Kliegl et al. (2006) of opposite effects of the predictability of word n and word n+1 on fixations on word n. To sum up, none of the criticisms of parafoveal-on-foveal effects stand up to scrutiny, and the conclusions of Experiments 2 and 4 in favour of parallel lexical processing during reading (such as that implemented in SWIFT) seem justified.

However, as mentioned above there are also inconsistencies within the experiments carried out for this thesis that do not support these conclusions. The first of these comes from the results of Experiment 3 that was a repetition of the orthographic priming paradigm of Experiment 2 but with the experimental stimuli located at position n-1. This experiment produced no effect of the orthographic relatedness of word n-1 on the fixation pattern recorded for word n. There are two possibilities as to why this might have occurred: either there is no lexical processing of word n-1 once lexical processing of word n has commenced, or there is parallel lexical processing of words n-1 and word n that was not detected by this experiment. The former explanation is in contrast to the predictions of SWIFT (Engbert et al., 2002, 2005; Richter et al., 2006) as processing in this model is distributed across four words around the fixation point that include the word to the left of fixation. It might be that SWIFT is incorrect in this assumption, and that our learned direction of reading directs our attention so strongly to the right of fixation that any words to the left of the current word are ignored. This is in line with the serial lexical processing mechanism of E-Z Reader that only allows for lexical processing of word n-1 in the unusual situation of the eyes moving to word n prior to full lexical access of word n-1 (Binder et al., 1999). However, even if this is the case it does not follow that there is no parallel processing of lexical information to the right of fixation, as indicated by Experiments 2 and 4.

The second possibility for the null findings also contains some merit. Work by Kliegl et al. (2006), Kliegl (2007), Pynte and Kennedy (2006) and Starr and Inhoff (2004) all points to the fact that some properties of word n-1 can affect fixations falling on word n. The study most similar to Experiment 3 is that of Starr and Inhoff (2004) who found that illegal orthography to the left of fixation increased first-pass fixation durations on word n. The question arises as to why no effect of word n-1 was apparent in Experiment 3, and this could follow the criticism of Rayner and colleagues discussed above that parafoveal-on-foveal effects are limited to sub-lexical influences. However, the studies by Kliegl and colleagues and Pynte and Kennedy demonstrated that lexical effects of word n-1 can be detected in the eye movement patterns on word n, and a likely reconciliation of these discrepant findings comes from their use of eye movement corpora with far more statistical power than Experiment 3. Whichever of these possibilities is assumed to be correct, neither dismisses the case for parallel lexical processing during reading. The former suggests that SWIFT might be incorrect in its assumption that the processing gradient extends to the left of the current word, and the latter suggests that any parallel lexical processing of words n and n-1 is attenuated compared with that of words n and n+1. Both of these possibilities are due to the strong ‘pull’ towards the upcoming word, which in English is the word to the right of fixation. An interesting follow-up experiment would be to compare the parafoveal-on-foveal effects recorded to the left and right of fixation in a language whose reading direction runs from right to left, such as Hebrew. Following the work by Pollatsek et al. (1981), it seems likely that the asymmetry reported in Experiments 2 and 3 would be reversed in a right-to-left language.

The results of Experiment 5 also did not support the case for parallel processing. Experiment 5 was an innovative experiment designed to test whether the fact that words are processed in conjunction with surrounding words during text reading is evident in our responses to isolated words. It therefore involved an isolated word lexical decision task but with the word flanked by bigrams that formed a plausible or implausible letter context (in a variation on the FLLD task). The findings from this experiment did not indicate that the plausibility of the flanking letter context affected lexical access, and thus provide no support for the theory of parallel processing. However, the logic of this experiment required an extrapolation from the theory of parallel processing as a strategy for efficient reading, to the hypothesis that parallel processing conditions the representation of words such that our responses to them in isolation are affected by text-level factors (rather than by orthographic priming from related letters, as in the orthographic FLLD paradigm). Once again, the null finding from this experiment does not cause the dismissal of the concept of parallel processing during reading, but rather implies that its utility as a reading strategy does not impact isolated word processing.

As above, the second possible explanation for this null finding is that this experiment did not detect the effect of more or less plausible flanking letters. This experiment was based on the concept of transitional probability that measures the statistical likelihood of the co-occurrence of two specific words (McDonald and Shillcock, 2003a, b) but due to the technical limitations discussed previously instead used bigrams that formed a letter context whose plausibility was not specific to the word undergoing lexical decision. A repetition of this experiment that compared the highest and lowest transitional probabilities specific to the word under consideration would provide a better test of the theory that readers use their implicit knowledge of word co-occurrence as an aid to more efficient reading. Despite the null findings, this experiment still demonstrated the utility of the Flanking Letters Lexical Decision task as a bridge between isolated word processing and text reading, as it allows transitional probability to be tested separately from contextual predictability that relies upon text-level knowledge.

Theoretical implications: Slot-based coding

The second main topic under consideration in this thesis concerns the appropriate letter input mechanism during lexical access. While older models of lexical access typically relied on slot-based coding of letters in which letter identity and letter order were coded conjunctively (e.g., Coltheart et al., 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap et al., 1982) recent findings on the effects of transposed-letters primes have led modellers to propose novel and more flexible input systems (e.g., Davis & Bowers, 2006; Gómez et al., submitted; Grainger et al., 2006; Shillcock et al., 2000; Whitney, 2001). The results of Experiments 1 (and 6) and 4 continue this trend away from strict slot-based coding as they demonstrated priming from primes whose letter identity but not order matched that of the target words.

Experiment 1 presented a novel form of priming that differed from typical priming experiments (e.g., Forster & Davis, 1984) in its simultaneous presentation of prime letters and response target, a presentation termed spatial priming in contrast to the typical prime and subsequent presentation of the target termed temporal priming. The reduced lexical decision response times in the two related letters conditions indicate that letter information is extracted from across the visual field. There was no difference recorded between the two related bigrams conditions that differed only in whether the order of the related letters matched that of the central word or not. This emphasises the importance of letter identity in lexical access, an emphasis corroborated in the growing body of work on extreme transposition primes (Grainger et al., 2006; Guerrera & Forster, 2008; Perea & Lupker, 2003, 2004; Whitney & Cornelissen, 2008).

Experiment 4, too, emphasised the role of letter identity in lexical access, this time during text reading. The exact processes that underpin word recognition during reading are often not clearly outlined by modellers, who rely instead on assuming that these processes are identical to those that take place during isolated word recognition (Radach & Kennedy, 2004). The comparison of transposed- and substituted-letters parafoveal primes in this experiment allowed it to address the question of whether slot-based coding of letters takes place during reading, following the logic of Johnson et al. (2007). The finding that substituted-letters primes were less effective than transposed-letters and identical primes echoes the finding from Experiment 1, and leads to the conclusion that slot-based coding is not appropriate during lexical access.

The widespread use of slot-based coding in early word recognition models comes from its accuracy and its implementation in the influential IAM (McClelland & Rumelhart, 1981). Its primary advantage is clear: the processing of the identity of every letter only within its slot eliminates the orthographic ambiguity that comes from a language of around one-quarter of a million words dependent on 26 written characters. In this way, anagrams such as *read* and *dear* can never be confused at the letter level. However, this advantage does not compensate for the inefficiency this system exhibits, and the results of multiple experiments including Experiments 1 and 4 of this thesis require any modeller to provide an alternative letter input mechanism. Several have risen to the challenge with a range of creative and experimentally-supported approaches, including open bigrams (Overlap Open-Bigram model; Grainger et al., 2006; SERIOL; Whitney, 2001), split-field grouping (split-fovea model; Shillcock & Monaghan, 2001) and spatial coding (SOLAR; Davis & Bowers, 2006).

This thesis cannot distinguish between these approaches, and future work will almost certainly take advantage of their differing predictions for exterior letters and extreme transpositions. So far, comparison of the models' performance on these effects (and others) have provided mixed results (Davis & Bowers, 2006; Grainger et al., 2006; Guerrera & Forster, 2008; Lupker et al., 2008; Perea & Lupker, 2003, 2004; Whitney & Cornelissen, 2008). However, one further tentative conclusion from Experiment 1 is that there was no support for the assumption of the SERIOL model (Whitney, 2001) that exterior letters play an enhanced role in lexical access. The Reversed condition of Experiment 1 disrupted the order of both internal and external prime letters with no impact upon processing speed of the target word, although for clarity future experiments should hold constant the order of either the interior and exterior letters separately. Other topics for consideration include further variations of the FLLD task, such as the number of letters of overlap between the central word and flanking bigrams required to induce priming, and the eye-movement pattern produced during eye-tracking of the central word (similar to Vitu et al., 2004). Spatial priming is in its infancy, and experiments such as these will help to elucidate how the presence of parafoveal information influences central word processing.

Linking isolated words and text reading

Throughout this thesis, the experiments have been designed to provide a link between the traditionally separate areas of lexical access during isolated word recognition and the eye-movement pattern produced during text reading. As discussed in the Literature Review, there are several ways that the connections between these topics could be researched. One is to investigate whether the same effects can be found in isolated words and in text reading (e.g., lexical frequency; Schilling et al., 1998) as this provides evidence as to whether similar processes underpin lexical access in both tasks. Related to this is an investigation of those effects that do not co-occur and the reasons for this, to isolate those processes specific to the task demands of lexical decision, naming, and reading for comprehension. This might include comparison with non-words, the vocalisation of speech, and acuity constraints respectively. Thirdly, there is the question of whether any specific model of word recognition can be incorporated into a model of text reading, as reading-level models have typically under-specified their lexical access component.

Starting with the first method, Experiments 1, 2 and 4 all demonstrate that orthographically related information present in parafoveal vision primes foveal lexical access and reduces either response times or viewing durations. In Experiment 1 the spatial priming of the Flanking Letters Lexical Decision task is the single word analogy of parafoveal-on-foveal effects, as this paradigm presents foveal and parafoveal information simultaneously. This is similar to the work on parafoveal preview by Rayner and colleagues that used the boundary paradigm to assess how much information is integrated across fixations for isolated words (e.g., Rayner et al., 1978) and during reading (e.g., Balota et al., 1985), although the work in this thesis concentrates on how much information is integrated within one fixation. Turning to method two, although Experiment 3 used a similar technique to Experiments 2 and 4, it provided no evidence for parafoveal orthographic priming. This is an example of how text-level factors can affect word processing: it seems likely that no orthographic priming effect was detected because the prime was positioned opposite to the direction of reading i.e., to the left of fixation. One way to confirm this hypothesis would be to carry out an amended version of the Orthographic FLLD task with the bigrams presented to only the right or left of the fixated word, with the prediction that the priming effects should be similar.

Method three formed the basis of Experiment 4, which combined the approaches of Experiments 1 and 2 to assess slot-based coding during reading. It utilised the sentence reading paradigm of Experiment 2 but included the comparison of identical and transposed-letters primes of Experiment 1, as well as a substituted-letters prime condition. Experiment 1 had already provided evidence against slot-based coding as a letter input method in a lexical decision task, and thus ruled out models such as the IAM (McClelland & Rumelhart, 1981) as inappropriate for isolated word recognition. Experiment 4 showed that the letter input process during reading is more flexible than a slot-based coding system would allow, and thus implies that these models are also inappropriate for the lexical access component of a text reading model. Experiment 4 is, arguably, the most important experiment presented in this thesis; Experiment 1 added to the existing large body of work clearly demonstrating that slot-based coding does not occur during isolated word recognition (e.g., Davis & Bowers, 2006; Guerrera & Forster, 2008; Perea & Lupker, 2003, 2004; Whitney & Cornelissen, 2008), but Experiment 4 extended these findings to a text scenario.

The results of Experiments 1 and 4 do not support slot-based coding, but beyond this they cannot distinguish between the five major recent models of isolated word recognition: SERIOL (Whitney, 2001), discrete open-bigrams (Grainger & van Heuven, 2003) SOLAR (Davis & Bowers, 2006), the overlap model (Gómez et al., submitted) and the split-fovea model (Shillcock & Monaghan, 2001). One way to distinguish between them might be to follow the example of Johnson et al. (2007) and Experiment 4 and assess each model's suitability as a template for lexical access in reading. This would involve including exterior letter, non-adjacent or extreme transposition primes as parafoveal words in a parafoveal preview or parafoveal-on-foveal experiment, as the models make differing predictions about the priming strength of these primes. For example, SERIOL (Whitney, 2001) emphasises the importance of exterior letter pairs over interior letters pairs for lexical access; evidence from the isolated word priming literature is mixed (Grainger et al., 2006; Guerrera & Forster, 2008). A similar debate as to the primacy of exterior letters also forms part of the parafoveal preview literature (Inhoff et al., 2003; Jordan, Thomas, Patching, 2003; Jordan, Thomas, Patching, & Scott-Brown, 2003). Even if future work using isolated words suggests that SERIOL is a viable candidate as a model of isolated word recognition, if parafoveal preview studies find that exterior letters do not have an enhanced role (presumably due to acuity limitations) then SERIOL cannot be accepted as a model of parafoveal lexical access without some amendments.

Experiments 5 and 6 continued the theme of linking isolated word recognition and reading by testing extensions of the original FLLD task. Experiment 5 showed how the

FLLD paradigm can act as a ‘snapshot’ of text while retaining the advantages of a tightly controlled and well-studied task. It demonstrates how this paradigm acts to separate letter-level effects from contextual influences, and thus falls in between the study of lexical variables (such as orthographic neighbourhood) and text-level effects (such as predictability). This experiment attempted to assess whether the simple presence of flanking words in text impinges upon our lexical representations and thus conditions our responses to unaccompanied words. Although it did not generate positive results it still represents a creative effort to bridge the gap between isolated word recognition and text reading. Experiment 6 included dyslexics as a comparison group to test the theory that dyslexics actually have an advantage over normal readers when it comes to processing letters at some eccentricity from the fixation point (e.g., Geiger & Lettvin, 1987). The advantage of the FLLD task in this case is that it moves beyond parafoveal letter recognition or even parafoveal word recognition to assess whether dyslexia affects the interaction between parafoveal letters and foveal words. This is more similar to a reading-type situation than the work by Geiger and colleagues, without requiring text reading that for dyslexics can represent a daunting and tiring task. The results imply that parafoveal processing does not represent a core advantage or deficit for dyslexics, and is an example of the utility of the FLLD task.

There are several other ways in which the ideas set out in this thesis could be expanded upon. All of the experiments carried out and most of the previous research discussed has used controlled experiments to compare different specific conditions, and an alternative approach is to make use of the data to be found in eye movement corpora recorded during realistic reading scenarios. This would provide a real-world perspective on whether orthographically similar parafoveal words affect fixated word processing as an indicator of the level of parallel lexical processing that takes place. Corpus work requires that variables such as word frequency, predictability, length etc. of the foveal and parafoveal words are included as factors in any analysis, and the measure of orthographic overlap chosen would have a serious impact upon the outcome. Those in favour of controlled experiments that alter only a few variables point out that it can be difficult to clearly attribute variance in a correlational analysis (e.g., Rayner, Pollatsek, et al., 2007) but the counter-argument states that combining the findings from corpora with those from experiments (and from computer simulations) increases the likelihood of reliable and sound conclusions (e.g., Kliegl, 2007).

Experiment 4 extended the word n+1 orthographic priming paradigm of Experiment 2 by using non-word primes that had more or less orthographic overlap with the target word but whose visual similarity was controlled in order to exclude the possibility that it was visual rather than orthographic relatedness between the prime and target that caused the parafoveal-on-foveal priming effect. An alternative method of ensuring that at least part of the priming effect was located beyond the visual level is to employ case alternation of the parafoveal word to disrupt the visual similarity of the prime and target but retain their orthographic similarity. Figure 46 illustrates a potential experimental setup. Following the findings of Experiment 4, the prediction would be that the Alternation condition should provide as much priming as the Repeated condition, both of which should provide more priming than the Control condition. This would act as a further demonstration of parallel orthographic processing during text reading.

The store had a *coat* | *coat* that week *(Repeated)*

The store had a *coat* | *CoAt* that week *(Alternation)*

The store had a *coat* | *milk* that week *(Control)*

FIG. 46: The potential case alternation version of Experiment 4 (target, parafoveal and post-boundary words in italics; the dashed line indicates the boundary position)

One way to explore the relationship between single word priming and priming during reading is to compare the neural characteristics of both experiences. Pernet et al. (2007) carried out a magnetoencephalography study of foveal and parafoveal priming and found that the neural correlates of the two tasks were similar in their activation areas and timings, indicating the similarity of the behavioural processing. These effects were bilaterally distributed for foveal primes, left-lateralised for the right visual field parafoveal primes and non-existent for the left visual field parafoveal primes, a distribution pattern that is almost certainly due to the left-to-right direction of English reading. Pernet et al. presented the foveal stimuli after the parafoveal stimuli, whereas this thesis has concentrated on simultaneous presentation so it would be interesting to extend this type of comparison to include spatial priming. Given the similarity of the conclusions for Experiments 1 and 2 the prediction is that the neural representation of these tasks would overlap considerably, with the exception of primes presented to the left visual field (see Experiment 3).

Lastly, a side-line that could be of great interest to any researchers employing a version of the boundary paradigm concerns the differing fixation locations of the two eyes. The boundary paradigm involves altering the information presented on screen when the selected eye (typically the right eye) crosses an invisible boundary; the tacit assumption of this paradigm is that the unselected eye is fixating on the same point as the selected eye, and thus that the information received by both is identical. What, however, are the ramifications for the boundary paradigm if the eyes are not conjointly fixated? If the unselected eye is fixating on a point ahead of the selected eye, it is possible that it is previewing the post-boundary information before the boundary change occurs, and thus any conclusion that upcoming information is processed in parafoveal vision might be incorrect. Figure 47 illustrates this point. If the eyes are conjoined or uncrossed (left eye further to the left than the right eye) then the information received by the selected right prior to the boundary change is as expected by the experimenter, and any parafoveal preview benefit received is due to pre-processing of the post-boundary word in parafoveal vision. However, in the case of the eyes being crossed (left eye further to the right than the right eye) the post-boundary word no longer falls only in parafoveal vision but rather in the foveal vision of the left eye, and any parafoveal preview benefit can also be attributed to simultaneous processing of the two words.

```
The cat jumped when the dog growled          (conjoined)
                     LR
The cat jumped when the dog growled          (uncrossed)
                   L  R
The cat jumped when the dog growled          (crossed)
                      R  L
```

FIG. 47: the effect of conjoined and non-conjoined fixation positions on the boundary paradigm; the dashed line indicates the position of the invisible boundary and the L and R indicate the position of the left and right eye respectively

Evidence as to the direction of non-conjoined fixations is mixed at present, but all research carried out using binocular eye-tracking of the positions of both eyes has indicated that some proportion of fixations do not fall on the same letter, with an average fixation disparity of 1.1 letters (Heller & Radach, 1999). The finding by Liversedge and collegaues (Blythe et al., 2006; Juhasz, Liversedge, White, & Rayner, 2006; Liversedge, Rayner, White, Findlay, & McSorley, 2006; Liversedge, White, et al., 2006) is of more uncrossed fixations than crossed fixations, whereas Shillcock and colleagues have recorded more crossed than uncrossed fixations. An experimental way to add to this debate would be to occlude the left eye during eye-tracking of boundary paradigm: if parafoveal preview benefit is reduced it implies that this was due to post-boundary processing by the left eye. This would require a re-think of models such as E-Z Reader (Reichle et al., 1998) that depend upon the results of parafoveal preview experiments as evidence for attention shifting. In contrast, in a parallel processing framework the mechanism by which orthographic information reaches the language systems is not strictly prescribed, and does not necessarily have to come from one eye only. However, the size of an effect of non-conjoined fixations is likely to be small, small enough that it would not provide an alternative explanation for the results presented above.

Conclusions

This thesis combines two slightly distinct topics: the characterisation of attention when reading, and the letter input coding mechanism for lexical access. The results of the experiments carried out to address these two topics lead to a model of reading whose word recognition 'module' does not code letters in terms of both their identity and position but rather places more emphasis on letter identity, and in which lexical access can take place for all words within the effective visual span simultaneously. In terms of existing models, this would be approximated by a combination of SWIFT (Engbert et al., 2002), and SOLAR (Davis & Bowers, 2006) or any other recent word recognition model whose input mechanism is more flexible than the traditional slot-based coding system. It is this notion of flexibility that links these two topics: the idea that when we read, information is there for the taking on the page or screen. It seems counter-productive to produce models whose information-processing capabilities are limited by word boundaries (in the case of reading) or letter order (in the case of lexical access).

There are several reasons to suggest that these limitations are unwarranted. Within a word, letter information does not have to be perfectly specified for reading to proceed (Grainger & Whitney, 2004), and word boundaries are not essential for normal reading behaviour (Epelboim, Booth, & Steinman, 1993; Yang & McConkie, 2004).The attention-shift mechanism implemented in E-Z Reader limits the span of attention to one word at a time, effectively terminating processing at the blank spaces that delineate written words, in much the same way that we segment words when listening. Kennedy (2003) noted that the implicit assumption in serial models is that words are individual 'objects' and should be treated as such. This 'reification' of the word reveals the commitment of modellers such as Rayner and colleagues to English in which word order is paramount and word structure changes little. Even English words can undergo contractions (*can't*) and combinations (*blackboard*), and languages other than English present even more of a problem. For example, Finnish is well-known for its long compound words (e.g., *autoissammekin*: *even in our cars*), and the contraction of *le* or *la* for *l'* that is attached to the start of the upcoming word is very common in French. Neither Finnish nor Russian follows a strict word order. It is not clear how a model such as E-Z Reader could be extended to such languages, and the flexible information extraction approach of parallel processing appears to be more appropriate in this extended capacity.

So why do some modellers limit their models with strict slot-based coding or serial attention shifting? The reason for the former was described in the discussion of slot-based coding above: conjunctive coding of letter order and identity eliminates any lexical ambiguity at the point of letter input. The inefficiency of this method was quickly realised and recent models of word recognition recognise that we place more emphasis on correct letter identity than order. The reason for insistence on the latter method is more subtle. In a language such as English in which word order is important for semantic comprehension, processing each word in turn imparts the printed word order directly to the reader without requiring any additional mechanisms. Reichle et al. (2003) pointed out that serial processing is required to preserve the temporal order of words, linking reading with speech processing that is necessarily more or less serial in nature. This link is made more explicitly by Pollatsek et al. (2006) who claim that the goal of reading is to convert written words into a representation of speech, as this is the form of language that the human brain has evolved to understand.

This link was rejected by Kennedy (2003) who noted that reading is a spatial rather than temporal activity, allowing sampling and re-sampling over a continuously present source of information. Parafoveal preview, spillover and regressions are common features of the eye movement patterns recorded during reading. This is completely unlike speech which is necessarily inflexible as one cannot re-hear previously spoken words or pre-hear those yet to be uttered in a way comparable to reading. Is it likely that an experienced reader (who has many years of practising an everyday task) does not take advantage of the opportunity to flexibly process as much information as possible during any one fixation? It seems theoretically improbable that there is never any simultaneous processing of multiple words, or that letter identity only aids lexical access when it is bound with letter order, and the results of this thesis seem to support this theory. The very fact that word order is important in English leads to clear predictions for the identity of upcoming words, and repeated exposure to language means that the experienced reader is very unlikely to confuse word order even if it is not perfectly preserved due to parallel lexical input. It would be unsurprising to find that reading proceeds in a more serial fashion for the novice reader, but the conclusion of this thesis is that proficient readers avail themselves of all of the visual, orthographic and lexical information present during a fixation.

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Appendices: Appendix 1

Word lists for the Orthographic and Dyslexia Flanking Letters Lexical Decision Task

High frequency words

away	from	look	such
back	full	love	sure
body	give	made	take
both	half	many	tell
case	hand	mind	them
city	have	miss	then
cost	high	most	they
each	just	much	true
even	keep	must	turn
ever	kind	need	very
face	know	next	want
fact	last	open	when
feet	left	over	wife
felt	less	part	will
find	life	room	with
five	like	said	work
form	line	seen	year
four	long	side	your

Low frequency words

aura	duct	gull	prim
avid	duet	guru	puff
bide	dune	gush	pyre
boar	fawn	harp	rend
cask	fern	iced	rift
chum	feud	jade	romp
clap	flee	kite	runt
claw	flog	laze	shun
clod	flop	lurk	smog
coax	fowl	lute	surf
cosy	fray	malt	swum
cuff	fret	mash	thug
dank	frog	moth	tint
deem	gash	muck	tuba
dial	gist	perk	veal
dire	glib	plum	wand
diva	glum	poke	womb
drip	gnaw	pout	yoga

Non-words

kish	arve	nurn	zish
yock	moid	koid	haff
bolf	mang	zede	gued
suth	mife	sule	bude
alse	wass	cank	yast
cipe	kere	chac	jote
urst	kest	skap	lazz
tich	sech	graw	coys
knen	sest	skod	vork
suce	nent	cout	jete
fice	nelf	coze	marn
falf	hien	curp	nush
feep	yote	gank	lith
fect	tert	dend	loal
fise	rete	blal	gark
ceve	yoom	zere	plac
tarm	sase	dizz	dake
tark	feen	duip	hins
fros	oked	vict	prak
moom	mide	durn	slig
nall	erch	bune	zore
yeve	shen	cewn	rese
halk	roke	feft	dype
hase	sull	ferb	womp
mave	clet	flot	nint
opes	thea	fliz	shub
nyst	thom	vipe	smib
keet	thid	foud	suib
ghem	jolf	frod	prum
junt	stry	frep	thim
urve	wace	frib	tilk
seft	fren	pesh	eant
sess	wice	tyst	clev
lind	wive	glog	veck
deke	sath	yatt	shem
lown	rork	glaw	tamb
lood	plar	zill	yoft
lich	wote	zimp	yoil

Appendix 2

Experimental sentences for the Repeated Word n+1 Parafoveal-on-Foveal Task: 4-letter target words

Target word in bold, post-boundary word in italics, Control word in parentheses

The proud parents watched as their **baby** *grew* into a toddler (fund)
Local police reported a **body** *seen* floating in the nearby river (week)
She enjoyed reading at night and kept a **book** *near* her bed (idea)
His leather **case** *felt* very soft because it was so old and worn (four)
A blacksmith's job is to **cast** *iron* to make horseshoes (pull)
The department store was having a **coat** *sale* that week (milk)
It's important to **cook** *meat* properly to avoid illness (wave)
Although the sun shone brightly a **cool** *wind* blew hard (vast)
The fishermen looked for a **deep** *pool* but there were none (firm)
Gamblers often **deny** *luck* is involved when they win (shut)
The gardener built a shed with a **dirt** *path* for access (loan)
The prince rode to the castle to end the **evil** *rule* of the wizard (warm)
Her wedding ring was a beautiful **gold** *band* with a diamond (tiny)
To make pottery you have to **heat** *clay* in an oven (sign)
She watched the **hero** *risk* his life to save the drowning boy (till)
The mountainous **hill** *camp* was only accessible by foot (song)
They camped by the **huge** *lake* under the stars (sick)
They **hung** *onto* the galloping horse for dear life (wore)
The court stood as the **king** *rose* to his feet (post)
I'll take a closer **look** *next* time I go to the exhibition (city)
My friend lost her purse and I don't want to **lose** *mine* as well (draw)
I can easily recover my **lost** *data* from the backup files (dead)
The landing was the **main** *test* of the pilot's ability (poor)
I try to keep my **mind** *open* to new experiences (area)
The editor told the **news** *unit* to cover the hostage crisis (film)
As the **pale** *moon* rose the owls began to hunt (soft)
I gave my little sister a sparkly **pink** *ring* for her birthday (holy)
Does my hotel **room** *face* the sea or the garden? (side)
During the summer monsoon the **rain** *beat* down every day (foot)
Good grapes are used to make the **rich** *wine* of France (fast)
You need to be on the **road** *soon* to arrive before dark (type)
The markets still **seem** *full* of people wanting to buy produce (turn)
Pet shops often **sell** *seed* for feeding garden birds (tour)
The sports **show** *gave* an exclusive report about the match (feet)
People with fair **skin** *tend* to burn more easily in the sun (poem)
She stood in the shade of a **tall** *tree* by the river (pure)
The architect showed the new **town** *plan* to the councillors (girl)
Suddenly a huge **wild** *bear* growled in the forest (busy)
The carpenter made chairs with the **wood** *sold* by the farmer (item)

Despite the happy ending I **wish** *none* of this had happened (lack)

Experimental sentences for the Repeated Word n+1 Parafoveal-on-Foveal Task: 5-letter target words

Target word in bold, post-boundary word in italics, Control word in parentheses

Airlines no longer **allow** *metal* objects to be taken on flights (enter)
Taking vitamin c will help you **avoid** *minor* illnesses (trust)
The opera singer's voice could **break** *glass* as it was so high (touch)
The diner moved his **chair** *aside* to let the waiter get past (stone)
He listened to the **daily** *radio* station while in the shower (green)
I had to hire a **dozen** *extra* chairs for my house party (grass)
That expensive **dress** *ought* to be kept for a special occasion (block)
She really liked to **drink** *fresh* juice in the mornings (watch)
He laid the **empty** *rifle* down and reached for his pistol (frank)
The warrior had finally found an **enemy** *equal* to his powers (sight)
The comedian gave a **funny** *reply* to the interviewer's question (rapid)
Every year the **grand** *opera* company tours smaller theatres (loose)
The angry security **guard** *threw* out the noisy teenagers (limit)
His painting portrays a **happy** *scene* of children playing (civil)
Darwin carried out the first **known** *study* of animal evolution (heard)
I took the **motor** *apart* to see why it wasn't working (uncle)
Her first **novel** *ended* up at the top of the bestseller list (birth)
The new travel agent will **offer** *fully* independent holiday advice (build)
The war leaders must come to the **peace** *table* to negotiate (third)
The nanny fed the naughty boy only **plain** *bread* and water (sorry)
The very high **price** *meant* I couldn't afford the new phone (mouth)
Should I give my flat a **quick** *clean* before my guests arrive? (gross)
War can shatter the **quiet** *lives* of those living in its shadow (round)
Hessian is a **rough** *cloth* used to make sugar sacks (blind)
You really need a **sharp** *knife* for cutting meat cleanly (fifty)
The medical **staff** *lived* at the hospital during the epidemic (blood)
The heavy **truck** *shook* as it crossed the cobbled bridge (goods)
The angry trade **union** *wrote* to the manager about pay cuts (space)
My gran will **visit** *ahead* of schedule to surprise my sister (reach)
The broken **wagon** *wheel* lay in front of the farmer's door (theme)

Filler sentences for the Repeated Word n+1 Parafoveal-on-Foveal Task

The keen birdwatcher spotted a rare eagle in its nest
The postman had to carry a heavy load of mail this morning
The holiday resort was a mere three miles from the beach
She will have to buy a new pair of shoes to match her dress
You can improve poor soil by adding fertiliser
They found a sunny spot in the park for their picnic
He didn't feel very safe climbing the mountain with no rope

The guard had to report for duty early because of the alert
I would prefer to grow vegetables rather than buying them
The pupil opened his desk to take out his maths textbook
The small boat was tossed violently in the stormy seas
Although they liked jazz they enjoyed the rock concert
The farmer's wife collected the eggs that the hens had laid
The teenager thought his younger sister was a pain in the neck
The little boy fell over in the playground and hurt his knee
They started the meal with thin slices of smoked salmon
They had to wait a long time for the bus to arrive that evening
It is easy to forget that we didn't always have computers
Do you think the gap is wide enough for my car to get through?
The model had beautiful blue eyes and a perfect smile
It was a pleasure to meet your mother last week
Only very fine thread is used to make the best cotton
She loved to read detective stories and crime novels
Their new house has a beautiful view out across the bay
That piece of toffee was so hard that I almost broke my tooth
She will be hard to miss in her neon jacket and trousers
She double-checked the doors to make sure they were locked
He used a ruler to draw a neat straight line across the page
I really want the new designer handbag I saw in the magazine
Not long ago people knew for certain that the Earth was flat
Her stripy green jumper didn't match her red skirt at all
Everyone was hooked on the gripping new television drama
There is a new trend to cycle to work rather than drive
The parents were very proud of their hardworking daughter
The football team wanted to prove that they were the best
In spite of everything the couple still loved each other
Some people prefer the taste of red wine more than white
I had a terrible dream last night about monsters chasing me
She enjoyed her hobby of collecting antique china figurines
Do you prefer the upper bunk or the lower one?
He always wanted to go into event management as a career
The river swept in a broad curve around the forest
They learned how to do the tango in their dance class
The newlyweds spent their honeymoon on a tropical island
The rich girl kept her pampered horse in a large grassy field
Nowadays most of our energy comes from crude oil
I prefer to use recycled paper whenever possible
I'll make my decision on the basis of current information
I cut my hair very short as it's easier to take care of it
He moved to a new house very close to where he used to live

Appendix 3

Experimental sentences for the Repeated Word n-1 Parafoveal-on-Foveal Task: 4-letter target words

Target word in bold, pre-boundary word in italics, Control word in parentheses

Her wedding ring was a beautiful *gold* **band** with a diamond (hole)
During the summer monsoon the *rain* **beat** down every day (hung)
The mountainous *hill* **camp** was only accessible by foot (song)
To make pottery you have to *heat* **clay** in an oven (sign)
He soon learned the *true* **cost** of buying a cheap car (wife)
The internet is a way to *move* **data** between people (hope)
The fishermen looked for a *pool* **deep** enough to catch carp in (firm)
The careless waiter let the *food* **fall** onto the floor (meet)
The markets still *seem* **full** of people wanting to buy produce (west)
The proud parents watched their *baby* **grow** into a toddler (save)
They had only *seen* **half** of the film when the projector broke (week)
Suddenly the climber *lost* **hold** of the sheer rock face (rest)
A blacksmith's job is to *cast* **iron** to make horseshoes (salt)
The geological survey found a *vast* **lake** under the mountain (fort)
It's important to *cook* **meat** properly to avoid illness (luck)
I try to keep an *open* **mind** when meeting new people (area)
My grandmother always *wore* **nice** hats and shoes (fast)
The executive had his restaurant *bill* **paid** for by his company (sent)
I gave my baby nephew a *tiny* **pair** of shoes for Christmas (soul)
The gardener built a shed with a *dirt* **path** for access (wire)
My boyfriend thinks that I don't *suit* **pink** clothes (holy)
The postmaster helped the old *lady* **post** her Christmas cards (gain)
The villagers could *draw* **pure** water from the nearby well (tall)
She watched the *hero* **risk** his life to save the drowning boy (pull)
The court stood as the *king* **rose** to his feet (laid)
He couldn't sleep because the man in the *next* **room** snored (city)
The prince rode to the castle to end the *evil* **rule** of the wizard (boat)
The department store was having a *coat* **sale** that week (inch)
Pet shops often *sell* **seed** for feeding garden birds (tour)
The farmer's wife has to *rear* **sick** lambs every winter (huge)
The cold weather made the *bear* **slow** and very grumpy (dear)
Luckily the novice skier fell *onto* **soft** snow and not ice (pale)
You need to be on the *road* **soon** to arrive before dark (hard)
People with fair *skin* **tend** to burn more easily in the sun (fill)
The landing was the *main* **test** of the pilot's ability (farm)
The editor told the *news* **unit** to cover the hostage crisis (role)
Every citizen wanted a free and *fair* **vote** for their new leader (bank)
She loves to *pick* **wild** berries from the highland forest (busy)

Although the sun shone brightly a *cool* **wind** blew hard (shop)

Experimental sentences for the Repeated Word n-1 Parafoveal-on-Foveal Task: 5-letter target words

Target word in bold, pre-boundary word in italics, Control word in parentheses

I took the *motor* **apart** to see why it wasn't working (loose)
Does the new city speed *limit* **apply** to country roads as well? (guess)
The diner moved his *chair* **aside** to let the waiter get past (truly)
The nanny fed the naughty boy only *plain* **bread** and water (pilot)
Hessian is a *rough* **cloth** used to make sugar sacks (drama)
He listened to the *radio* **daily** to hear his favourite show (wrong)
Good weather made the *crowd* **enjoy** the concert even more (catch)
The warrior had finally found an *enemy* **equal** to his powers (broad)
I had to hire a *dozen* **extra** chairs for my house party (blind)
She really liked to *drink* **fresh** juice in the mornings (civil)
The new travel agent will *offer* **fully** independent holiday advice (twice)
The opera singer's voice could *break* **glass** as it was so high (mouth)
He was not his *usual* **happy** self after he failed his driving test (older)
The executive *board* **heard** how the share price had fallen (known)
War can shatter the *quiet* **lives** of those living in its shadow (youth)
Airlines no longer *allow* **metal** objects to be taken on flights (quick)
I will make a CD of *party* **music** for my friend's surprise party (level)
The author wrote a daringly *frank* **novel** about love and loss (birth)
Every year the *grand* **opera** company tours smaller theatres (skill)
That expensive *dress* **ought** to be kept for a special occasion (armed)
The comedian gave a *funny* **reply** to the interviewer's question (match)
He laid the *empty* **rifle** down and reached for his pistol (coast)
You need to keep your *knife* **sharp** for cutting cleanly (fifty)
The heavy *truck* **shook** as it crossed the cobbled bridge (begun)
The large *angry* **snake** weaved dangerously in its cage (porch)
The new guard had to learn how to *stand* **stock** still on duty (paper)
The war leaders must come to the *peace* **table** to negotiate (sound)
The angry security *guard* **threw** out the noisy teenagers (bound)
The broken *wagon* **wheel** lay in front of the farmer's door (grass)
Criminals used to join the army to *avoid* **worse** punishment (vital)

Filler sentences for the Repeated Word n-1 Parafoveal-on-Foveal Task

The keen birdwatcher spotted a rare eagle in its nest
The postman had to carry a heavy load of mail this morning
The holiday resort was a mere three metres from the beach
You can improve poor soil by adding fertiliser
They found a sunny spot in the park for their picnic

He didn't feel very safe climbing the mountain with no rope
The guard had to report for duty early because of the alert
The pupil opened his desk to take out his maths textbook
Do you think the weather will be warm today?
The nervous jury took a long time to return their verdict
Although they liked jazz they enjoyed the rock concert
The teenager thought his younger sister was a pain in the neck
The girl worked very hard to pass her driving test
The little boy fell over in the playground and hurt his knee
They started the meal with thin slices of smoked salmon
They had to wait a long time for the bus to arrive that evening
We will stop at the hotel to break our journey
It is easy to forget that we didn't always have computers
Do you think the gap is wide enough for my car to get through?
The model had beautiful blue eyes and a perfect smile
Only very fine thread is used to make the best cotton
She loved to read detective stories and crime novels
Their new house has a beautiful view out across the bay
The raging fire burned all night with no sign of stopping
She will be hard to miss in her neon jacket and trousers
She double-checked the doors to make sure they were locked
He used a ruler to draw a neat straight line across the page
I really want the new designer handbag I saw in the magazine
His leather case felt very soft because it was so old and worn
Not long ago people knew for certain that the Earth was flat
The minister consulted the focus group for advice
There is a new trend to cycle to work rather than drive
The parents were very proud of their hardworking daughter
The football team wanted to prove that they were the best
In spite of everything the couple still loved each other
Some people prefer the taste of red wine more than white
I had a terrible dream last night about monsters chasing me
She enjoyed her hobby of collecting antique china figurines
Do you prefer the upper bunk or the lower one?
He always wanted to go into event management as a career
They learned how to do the tango in their dance class
The newlyweds spent their honeymoon on a tropical island
The very high price meant I couldn't afford the new phone
The rich girl kept her pampered horse in a large grassy field
Nowadays most of our energy comes from crude oil
The river swept in a wide curve around the forest
The angry trade union wrote to the manager about pay cuts
I'll make my decision on the basis of current information
I cut my hair very short as it's easier to take care of it
He moved to a new house very close to where he used to live

Appendix 4

Experimental sentences for the Transposed Letters Parafoveal-on-Foveal Task: 4-letter target words

Target word in bold, post-boundary word in italics, Transposed and Substituted stimuli in parentheses

The proud parents watched as their **baby** *grew* into a toddler (bbay, btoy)
The executive had his restaurant **bill** *paid* for by his company (blil, bfel)
Local police reported a **body** *seen* floating in the nearby river (bdoy, btey)
His leather **case** *felt* very soft because it was so old and worn (csae, cmee)
A blacksmith's job is to **cast** *iron* to make horseshoes (csat, ccit)
The department store was having a **coat** *sale* that week (caot, ciet)
Gamblers often **deny** *luck* is involved when they win (dney, dvuy)
The gardener built a shed with a **dirt** *path* for access (drit, dwut)
The prince rode to the castle to end the **evil** *rule* of the wizard (eivl, eanl)
Every citizen wanted a free and **fair** *vote* for their new leader (fiar, feor)
Her wedding ring was a beautiful **gold** *band* with a diamond (glod, gbad)
To make pottery you have to **heat** *clay* in an oven (haet, hoit)
She watched the **hero** *risk* his life to save the drowning boy (hreo, hxio)
The mountainous **hill** *camp* was only accessible by foot (hlil, hbul)
They camped by the **huge** *lake* under the stars (hgue, hqae)
They **hung** *onto* the galloping horse for dear life (hnug, hmag)
The court stood as the **king** *rose* to his feet (knig, kseg)
The neighbour helped the old **lady** *post* her Christmas cards (lday, ltiy)
My friend lost her purse and I don't want to **lose** *mine* as well (lsoe, lzue)
I can easily recover my **lost** *data* from the backup files (lsot, lvit)
The take-off was the **main** *test* of the pilot's ability (mian, meun)
The editor told the **news** *unit* to cover the hostage crisis (nwes, nmis)
He couldn't sleep because the man in the **next** *room* snored (nxet, nmot)
Luckily the novice skier fell **onto** *soft* snow and not ice (otno, olvo)
I try to keep an **open** *mind* when meeting new people (oepn, oajn)
As the **pale** *moon* rose the owls began to hunt (plae, pdoe)
I gave my little sister a sparkly **pink** *ring* for her birthday (pnik, pzuk)
During the summer monsoon the **rain** *beat* down every day (rian, roun)
Good grapes are used to make the **rich** *wine* of France (rcih, rveh)
You need to be on the **road** *soon* to arrive before dark (raod, ruid)
Pet shops often **sell** *seed* for feeding garden birds (slel, shul)
The sports **show** *gave* an exclusive report about the match (sohw, sibw)
People with fair **skin** *tend* to burn more easily in the sun (sikn, safn)
The carpenter also **sold** *wood* to make some extra money (slod, sbad)
She stood in the shade of a **tall** *tree* by the river (tlal, tbul)
The architect showed the new **town** *plan* to the councillors (twon, tcen)
Suddenly a huge **wild** *bear* growled in the forest (wlid, whad)

Despite the happy ending I **wish** *none* of this had happened (wsih, wnuh)
My grandmother always **wore** *nice* hats and shoes (wroe, wnie)

Experimental sentences for the Repeated Word n-1 Parafoveal-on-Foveal Task: 5-letter target words

Target word in bold, post-boundary word in italics, Control word in parentheses

Taking vitamin C will help you **avoid** *minor* illnesses (aovid, aawid)
The executive **board** *heard* how the share price had fallen (baord, buerd)
The opera singer's voice could **break** *glass* as it was so high (berak, bivak)
The diner moved his **chair** *aside* to let the waiter get past (cahir, cebir)
Good weather made the **crowd** *enjoy* the concert even more (corwd, camwd)
He listened to the **daily** *radio* station while in the shower (dialy, duoly)
I had to hire a **dozen** *extra* chairs for my house party (dzoen, dsien)
That expensive **dress** *ought* to be kept for a special occasion (derss, damss)
She really liked to **drink** *fresh* juice in the mornings (dirnk, doxnk)
He laid the **empty** *rifle* down and reached for his pistol (epmty, eqvty)
The warrior had finally found an **enemy** *equal* to his powers (eenmy, euvmy)
The comedian gave a **funny** *reply* to the interviewer's question (fnuny, fcony)
Every year the **grand** *opera* company tours smaller theatres (garnd, ginnd)
The angry security **guard** *threw* out the noisy teenagers (gaurd, gierd)
His painting portrays a **happy** *scene* of children playing (hpapy, hyepy)
Darwin carried out the first **known** *study* of animal evolution (konwn, kuxwn)
I took the **motor** *apart* to see why it wasn't working (mtoor, mbior)
Her first **novel** *ended* up at the top of the bestseller list (nvoel, ncael)
I will make a CD of **party** *music* for my friend's birthday party (praty, pvety
The war leaders must come to the **peace** *table* to negotiate (paece, pioce)
The very high **price** *meant* I couldn't afford the new phone (pirce, posce)
Should I give my flat a **quick** *clean* before my guests arrive? (qiuck, qaeck)
War can shatter the **quiet** *lives* of those living in its shadow (qiuet, qoeet)
Hessian is a **rough** *cloth* used to make sugar sacks (ruogh, reagh)
You really need a **sharp** *knife* for cutting meat cleanly (sahrp, sidrp)
The medical **staff** *lived* at the hospital during the epidemic (satff, solff)
The heavy **truck** *shook* as it crossed the cobbled bridge (turck, tewck)
The angry trade **union** *wrote* to the manager about pay cuts (uinon, uevon)
My gran will **visit** *ahead* of schedule to surprise my sister (vsiit, vcuit)
The broken **wagon** *wheel* lay in front of the farmer's door (wgaon, wyion)

Filler sentences for the Transposed Letters Parafoveal-on-Foveal Task

The keen birdwatcher spotted a rare eagle in its nest
The postman had to carry a heavy load of mail this morning
The holiday resort was a mere three miles from the beach
She will have to buy a new pair of shoes to match her dress
You can improve poor soil by adding fertiliser

They found a sunny spot in the park for their picnic
He didn't feel very safe climbing the mountain with no rope
I would prefer to grow vegetables rather than buying them
The pupil opened his desk to take out his maths textbook
The small boat was tossed violently in the stormy seas
Although they liked jazz they enjoyed the rock concert
The farmer's wife collected the eggs that the hens had laid
The teenager thought his younger sister was a pain in the neck
The little boy fell over in the playground and hurt his knee
They started the meal with thin slices of smoked salmon
They had to wait a long time for the bus to arrive that evening
It is easy to forget that we didn't always have computers
Do you think the gap is wide enough for my car to get through?
The model had beautiful blue eyes and a perfect smile
It was a pleasure to meet your mother last week
Only very fine thread is used to make the best cotton
She loved to read detective stories and crime novels
Their new house has a beautiful view out across the bay
The raging fire burned all night with no sign of stopping
That piece of toffee was so hard that I almost broke my tooth
She will be hard to miss in her neon jacket and trousers
She double-checked the doors to make sure they were locked
He used a ruler to draw a neat straight line across the page
I really want the new designer handbag I saw in the magazine
Not long ago people knew for certain that the Earth was flat
Her stripy green jumper didn't match her red skirt at all
Everyone was hooked on the gripping new television drama
There is a new trend to cycle to work rather than drive
The parents were very proud of their hardworking daughter
The football team wanted to prove that they were the best
In spite of everything the couple still loved each other
Some people prefer the taste of red wine more than white
I had a terrible dream last night about monsters chasing me
She enjoyed her hobby of collecting antique china figurines
Do you prefer the upper bunk or the lower one?
He always wanted to go into event management as a career
The river swept in a broad curve around the forest
They learned how to do the tango in their dance class
The newlyweds spent their honeymoon on a tropical island
The rich girl kept her pampered horse in a large grassy field
Nowadays most of our energy comes from crude oil
I prefer to use recycled paper whenever possible
I'll make my decision on the basis of current information
I cut my hair very short as it's easier to take care of it
He moved to a new house very close to where he used to live

Appendix 5

Word lists for the Context Flanking Letters Lexical Decision Task

High frequency words

away	from	look	such
back	full	love	sure
body	give	made	take
both	half	many	tell
case	hand	mind	them
city	have	miss	then
cost	high	most	they
each	just	much	true
even	keep	must	turn
ever	kind	need	very
face	know	next	want
fact	last	open	when
feet	left	over	wife
felt	less	part	will
find	life	room	with
five	like	said	work
form	line	seen	year
four	long	side	your

Low frequency words

aura	duct	gull	prim
avid	duet	guru	puff
bide	dune	gush	pyre
boar	fawn	harp	rend
cask	fern	iced	rift
chum	feud	jade	romp
clap	flee	kite	runt
claw	flog	laze	shun
clod	flop	lurk	smog
coax	fowl	lute	surf
cosy	fray	malt	swum
cuff	fret	mash	thug
dank	frog	moth	tint
deem	gash	muck	tuba
dial	gist	perk	veal
dire	glib	plum	wand
diva	glum	poke	womb
drip	gnaw	pout	yoga

Non-words

shen	zore	tyst	sess
yoil	thea	veck	fice
rete	mang	prak	tamb
kish	urst	frod	nent
lood	jote	cewn	jolf
bude	smib	tilk	plar
bolf	yoft	pesh	clev
thom	junt	ceve	yast
fros	opes	nyst	halk
wace	gued	koid	sase
womp	feen	kere	zede
suth	sath	kest	ferb
rese	glaw	dend	mife
wive	durn	yatt	dake
shub	ghem	fliz	zill
knen	mide	skap	marn
feft	fise	frib	stry
roke	nurn	bune	sull
plac	tert	graw	seft
keet	nush	vork	dizz
lind	lown	jete	lith
tarm	frep	glog	yeve
gark	thim	moid	coze
fren	fect	alse	prum
wass	blal	duip	sest
eant	hien	curp	zish
rork	sech	shem	yote
mave	sule	gank	lazz
chac	thid	arve	zimp
yock	cank	haff	suib
lich	foud	yoom	dype
vipe	nall	feep	hins
moom	nelf	hase	cout
loal	tark	wote	flot
skod	deke	oked	urve
clet	vict	cipe	tich

Appendix 6

Word lists for the word and non-word reading tests for the Dyslexia Flanking Letters Lexical Decision Task

Word reading test

Ocean	Sword	Drought	Bureau
Iron	Anchor	Trough	Circuit
Island	Echo	Depot	Schedule
Busy	Chorus	Aisle	Encore
Sugar	Dough	Bouquet	Heirloom
Truth	Ache	Foreign	Champagne
Whom	Ninth	Yacht	Distraught
Tongue	React	Chauffeur	Sovereign
Rhythm	Tomb	Sergeant	Righteous
Stomach	Vague	Suede	Benign
Wounded	Colonel	Gauge	Baroque

Non-word reading test

Chur	Skree	Cratty	Drepnort
Knap	Felly	Trober	Shratted
Tive	Clirt	Depate	Plofent
Barp	Sline	Glant	Smuncrit
Stip	Dreef	Sploosh	Pelnador
Plin	Prain	Dreker	Fornalask
Frip	Zint	Ritlun	Fermabalt
Poth	Bloot	Hedfert	Crendimoke
Vasp	Trisk	Bremick	Emulbatate
Meest	Kelm	Nifpate	
Shlee	Strone	Brinbert	
Guddy	Lunaf	Clabom	

Appendix 7

Poster published at the European Conference on Eye Movements, Potsdam, 2007

Crossed disparities are preferred over uncrossed disparities: evidence from binocular lexical decision in a stereoscope

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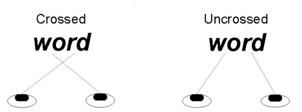
Introduction

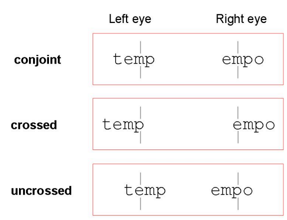
- Underpinning most current models of information extraction during text reading is the assumption that the two eyes are fixating on the same point.
- The recent advent of binocular eye-tracking techniques has allowed for questioning of this assumption (Heller & Radach, 1999).
- Binocular eye-tracking of reading has shown that the eyes are on average 1.1 characters apart (Liversedge, White, Findlay & Rayner, 2006).
- However, the direction of this disparity remains contentious, with some research showing that the eyes are crossed and some that they are uncrossed.



- For example, Liversedge et al. (2006) found that about 40% of fixations are uncrossed, with only about 5% crossed.
- Similarly, Juhasz, Liversedge, White, and Rayner (2006) found more uncrossed than crossed fixations, with the proportions unaffected by linguistic difficulty.
- However, analysis of the Edinburgh 5lang Corpus has shown that crossed fixations predominate.
- This is also true for other research, from other laboratories, using Eyelink tracking systems.

Method

- One problem with existing work is that fixation positions cannot be induced, only observed.
- Instead we presented words using a stereoscope which provides different information to each eye while simulating the percept of a coherent word.
- This allowed us to mimic the information seen in 3 fixation positions: conjoint, crossed and uncrossed.

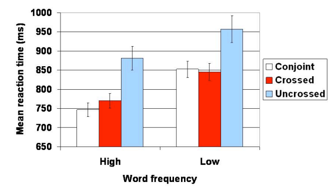


- 36 participants made a lexical decision to high and low frequency 5-letter strings presented for 80 ms.
- Complementary 4-letter parts of 5-letter strings were presented to ensure that participants had to fuse the two images.

Predictions

- If uncrossed fixations are favoured, responses will be faster in the uncrossed condition than in the crossed condition.
- If crossed fixations are favoured, responses will be faster in the crossed condition than in the uncrossed condition.

Results



- Linear mixed effects analysis showed:
  - main effect of word frequency [$F(1,142.68) = 47.90$,
  - $p < 0.001$]
  - main effect of fixation condition [$F(2,3162.25) = 51.49$,
  - $p < 0.001$]
- Responses in the uncrossed condition were slower than in the crossed condition [$t(3178.15) = 8.96$, $p < 0.001$].

Conclusions

- Crossed fixations seem to be preferred over uncrossed.
- What are the reasons for these different observations, and what are the implications of non-conjoint fixations for models of eye movement control during reading?

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